THE LIFE EXPECTANCY OF DENTAL RESTORATIONS PLACED WITHIN THE GENERAL DENTAL SERVICES IN ENGLAND AND WALES

by

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ABSTRACT

This study measured the distribution of the interval between placement and next intervention on the same tooth for direct restorations of teeth in the General Dental Services of the NHS in England and Wales between January 1991 and December 2002. Three different sets of treatment data covering the period were used, involving over 1.3 million restorations. Standard and modified Kaplan-Meier, and three different cross-sectional techniques were used to estimate empirical survival curves, and Cox-regression was used to model the relationship with risk factors associated with the dentist, the patient, geographical location, time, tooth position and type of restoration and cavity.

Overall, median survival was slightly more than eight years from placement to re-intervention. The rates of survival without intervention after one year, five years and ten years were, respectively, 89%, 62% and 46%.

Key risk factors associated with survival were type of cavity, tooth position, patient age, patient treatment history and patient attendance history. The underlying baseline function of the Cox-regression analysis was closely modelled by both a Weibull and a cubic function.

The robustness of the findings was demonstrated by a full replication of the eleven-year analysis using a completely separate fourth sample from the DPB’s data archive.

DEDICATION

This thesis is dedicated to the memory of the late Jean Todd, without whose vision and tenacity the data underlying this work would long ago have been lost.

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Finally, and not least, I would like to thank my wife and family for all the sacrifices they have endured to allow me to indulge my passion for this fascinating area of research.

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1.1 Description of the Problem

1.1.1 Directly Placed Dental Restorations

When faced with a tooth which is in some way damaged, whether by disease or by trauma, a dentist has a range of treatment options. Left untreated, some teeth may remineralise or, at least, they may deteriorate no further. At the other extreme, a tooth may be so badly damaged that the only option is to extract it and either leave the space unfilled, or restore the space with a denture, bridge or implant.

The intermediate treatment is to restore the tooth, replacing the missing or decayed parts with artificial materials, such as metals or polymers. This generally involves some preparation of the tooth, using a drill or other instrument. If the material used for filling the tooth is plastic when inserted into the tooth, and then shaped by the dentist in the patient's mouth, then the restoration may be described as directly placed.

The alternative is to prefabricate a rigid restoration in a laboratory, and to insert this into or onto a precise preparation on the tooth. Such indirectly placed restorations include crowns, inlays, and veneers.

This thesis is concerned with the life expectancy of directly placed dental restorations, generally referred to as 'fillings', the term which will be used in this work hereafter. Fillings may be used in any teeth, though teeth in different parts of the mouth have different functions, and therefore require different physical properties for materials used for filling. Posterior (back) teeth, namely molars and premolars, are used for grinding food, for which purpose the main requirements of fillings in these teeth are adequate physical properties, including compressive and tensile strengths and resistance to wear. Restorations on anterior (front) teeth, the canines and incisors, also require adequate physical properties but, as these teeth are important aesthetically, a tooth-coloured material is generally preferred for filling anterior teeth.

Various other treatments may be associated with a dental restoration, such as the placement of pins or screws to improve the retention between the restoration and the tooth. A particular type of directly placed restoration, namely a root filling, may also be used, to fill the root canals where it has been necessary to remove the pulp from the tooth. A root filling is not provided in isolation – it requires another restoration, direct or indirect, on the parent tooth.

1.1.2 Life Expectancy

A dental restoration has a finite useful life, bounded ultimately by the physical life of the patient in whose mouth the restored tooth resides. This life, and its component parts, can be defined in various ways. At one extreme are the first signs of deterioration of the restoration, even though remedial work is not immediately required. At the other, the deterioration may be so severe that an independent dental examiner agrees that remedial action is necessary. In some cases the restoration or surrounding tooth will fail catastrophically. An unrelated event, such as a trauma, might result in the loss of the tooth, albeit with the filling intact. A diagnosis of secondary caries, defined as lesions at the margins of existing restorations (Mjör and Toffenetti, 2000), may also prompt a further intervention on the tooth, leaving unanswered the question as to whether the original filling had failed, or merely the tooth supporting it, or whether active caries had been left in the original cavity, named as ‘residual’ caries by Kidd et al (1992).

Whatever the definition of the life of a filling, there exists a branch of statistical science which specializes in the study of life expectancy, and in particular of ‘survival curves’ and ‘hazard functions’ (Collett, 1994). Parallels to this problem of estimating the longevity of dental restorations can be found in many areas of medicine, science, and industry. The classical medical application is literal life expectancy of patients, generally those diagnosed as having particular diseases and receiving particular treatments. The same principles can however be applied to non-fatal episodes, such as the interval between the recurrence of symptoms, such as migraines or epileptic fits. Industrial applications include the intervals before failure of components in machines, and the whole field of associated economics concerned with alternative maintenance programmes.

The statistical techniques concerned with survival analysis address two issues. On the one hand, there is a battery of methods for estimating, with confidence intervals, empirical survival curves – the proportion of a population expected to survive for 1, 2, 3, … units of time – together with significance tests for testing the hypothesis that two populations have the same survival expectation. On the other, there are a range of theoretical functions to which, under certain assumptions, it may be expected that the survivor and hazard functions should conform. Armed with these functions, and techniques for estimating appropriate parameters, the researcher may develop parametric statistical models which not only fit the observed data but which have useful predictive power for as yet unobserved outcomes.

1.1.3 Interested Parties

Returning to the issue of dental restorations, it is useful to consider who may wish to know how long they will last, and what is their particular interest in acquiring this knowledge. In the case of a particular patient there are three obviously interested parties: the patient, the dentist, and any third party payer, such as the tax-payer - through the National Health Service (NHS) - or an insurance company. More generally, the suppliers of restorative materials have an interest, as have organizations responsible for the training of dentists and the advancement of dental science. In this latter category we could include the university dental schools, the Department of Health in England and its equivalent in Wales, and the UK General Dental Council. We will now consider the interests of these parties in turn.

The **patient**, whether he or she pays for the treatment or not, experiences inconvenience in attending the dentist's surgery for treatment, plus possibly pain or discomfort while the treatment is being provided. Before the restoration is first placed, and each time it is replaced, he or she may also experience pain, discomfort and possible embarrassment. To make an informed decision as to whether to agree to undergo a particular treatment, such as a directly placed restoration, the patient will wish to weigh the long term benefits as well as the immediate expected pain, discomfort, cost and aesthetics of that treatment against any alternatives (Sjögren and Halling, 2002). Before the advent of the General Dental Services in England and Wales (GDS), the treatment of choice was often extraction rather than filling, to avoid absolutely the prospect of future pain and cost associated with restoration of decayed teeth.

The **dentist** has his or her patients' interests at heart, and will wish to provide accurate information (Kay et al, 1995). The dentist will also wish to plan for the future development of his or her business. In the very long term, patients with standing teeth may be a better source of income than those without any teeth to maintain. Excessive or inappropriate restoration of teeth may hasten the onset of total tooth loss. Clinical audit and peer review are essential components in providing a professional dental service. If a dentist's fillings do not last as long as fillings provided elsewhere, particularly in an area with a similar catchment population, then he or she will have a professional concern to find out why – it may be that there is a need to review his or her own techniques or equipment.

The **tax-payer**, through the Dental Practice Board (section 1.3.2), is interested in obtaining value for money, expressed for example as the number of useful years of life provided for a tooth before further investment is required. If certain types of restoration, applied to certain teeth in certain circumstances, can be shown to offer poor value for money compared with alternatives, then this can be reflected either in guidance to dentists or in changes to the Statement of Dental Remuneration (SDR), an example of which was the removal of posterior gold crowns from the SDR in December 1998.

Other **third party** contributors to payment, such as insurance companies and indeed the NHS, need information about life expectancy of fillings to help in setting premiums to patients and fees to dentists and in deciding what treatments to include within their schemes (Bogacki et al, 2002). A more expensive restoration may offer lower long-term maintenance costs, and knowledge of where this is the case may enable a co-payer to offer more expensive short-term treatment at attractive long-term premiums.

The **Dental Practice Board** (DPB) is also concerned with the quality of work carried out within the GDS, and seeks to ensure that any dentist whose work is consistently below the standard reasonably expected, after taking other factors into account, is identified promptly so that remedial measures can be taken. To perform this role it is necessary, not only to measure the performance of an individual dentist, but also to have a statistical backcloth against which his or her performance can be compared. Examples can be found at the DPB's web site (such as DPB, 2002b).

Suppliers of restorative dental materials have an interest in how their materials perform in the real world, and what factors might influence their performance, compared with the results obtained in a laboratory. They also have a direct interest in their products' performance compared with that of their competitors' products, particularly if this information is made available to patients and dentists (Brochu and El-Mowafy, 2002).

Dental Schools seek to teach best practice, and continuously to improve the quality of treatment provided by their students (General Dental Council, 2002). A knowledge of which materials last how long, and in what circumstances, is valuable information to impart in the training of a dentist. From a research point of view, such information may act as a springboard to the discovery of new materials and techniques for improving the longevity of restorations.

The **General Dental Council** and the **Department of Health** (representing the Government) have a strategic interest in fostering all measures which will encourage the attainment of the Oral Health Strategy and the NHS Plan as it relates to dentistry (Department of Health, 2000), and in particular the retention as long as possible of natural functional dentition among the adult population. The long-term survival of teeth, under different restoration regimes, is of particular relevance to this objective.

1.1.4 What Constitutes the End of the Life of a Restoration?

Consider again the issue of life expectancy (see section 1.1.2). The start of the life of a filling is well defined as a point of time, when the filling is actually placed in the tooth. For practical purposes it may be acceptable to extend this to the date when the dentist discharges the patient at the end of the course of treatment as having received, under the terms of the GDS ‘all the care and treatment required to secure and maintain oral health’.

The end of the life of a filling is conceptually more difficult, and it also strays into the issue of censoring. An observation of a life is said to be censored if the time of the start, or the time of the end, is not known exactly, but can be placed within a time interval. Where the end time is known to be after a specified time, but without further limit, then the case is described as ‘right-censored’. In the case of the life of dental restorations, most censoring is of this type. There are many different reasons why such censoring may occur. If a patient, having been provided with a filling, goes away and does not come back, should this be regarded as a success, or a failure, or somewhere in between? If he or she returns for a check-up, and the tooth is sound and present, then it might be conceded that, so far at least, the filling has not failed, at least in the eyes of the dentist conducting the check-up. It is assumed of course that all the treatment data for the patient are available (that is, that no ‘unauthorised’ repair work has been carried out elsewhere).

If a filling requires replacement, it could be defined as having failed, though even here it may not be the filling itself which has failed, but something else about the tooth, such as an underlying root filling, which may even have been already present before the filling was placed. If a filling has failed completely, the remedial treatment may involve a larger filling, a crown, or, indeed, an extraction. A working definition of a failure will require a specification of the subsequent treatment which indicates failure, as well perhaps as that which indicates continuing healthy life. The literature contains a range of different definitions (for example Smales et al, 1991a, or Martin and Bader, 1997).

The above remarks have been made from the point of view of the dentist providing treatment. From the patient’s perspective, the need for remedial treatment becomes apparent only if he or she becomes conscious that a filling has fallen out or looks unsightly, or he or she experiences pain or other discomfort. Depending on the severity of the symptoms, the patient may contact his or her dentist immediately, or wait until the next routine check-up. If the need for repair is asymptomatic, the patient relies on the professional judgement of the dentist. However, it can be argued that one of the expectations of patients is that the number of unanticipated visits to the dentist will be kept to a minimum – the regular check-up should detect incipient failures before the patient becomes painfully aware of them.

The perspective of the person or organisation who pays for the treatment is also relevant. In terms of minimising the cost to the public purse, the patient who does not come back to any part of the NHS is a success. If the ideal is that fillings should restore teeth to their natural state, and that no natural tooth should be lost, then every re-intervention on a restored tooth is a failure, to the extent that it reduces the value, in years of useful tooth life, obtained from the original filling. From a public health point of view, the ideal would be that teeth never had to be treated in the first place, let alone retreated. Dentistry would ideally become a science of vigilant monitoring and prevention, rather than interventive reconstruction.

1.1.5 Dental Factors

In considering the life expectancy of a filling, many characteristics of that filling may be relevant (Jokstad et al, 2001). This section considers some of the dental issues which may be expected to have a bearing.

Consider first the tooth itself and the restoration proposed. The adult mouth has a complement of thirty-two teeth, sixteen in each jaw, ranging from anterior incisors and canines with edges which facilitate biting to large posterior molars and premolars for grinding. The dentist proposing the original restoration may be able to see and reach some teeth better than others (left hand / right hand, upper jaw / lower), which may affect both the decision to restore and the standard of restoration actually achieved. Similar considerations may apply to the replacement of the filling or other subsequent retreatment of the tooth. They may also apply to the patient, in the diligence with which teeth are cleaned. Because of the different functions of different teeth, and their interactions with the patient's diet, it is reasonable to expect that the level of wear and degradation on teeth will vary according to the position in the mouth.

Whatever the tooth, the size, shape and location of the cavity to be filled may be expected to be an important factor (Maryniuk and Kaplan, 1986). In principle, cavities could occur in any shape or size in any tooth, but the anatomy of teeth and the pattern of caries development are such that they can be classified into a small set of different classes. Perhaps the best known of these is that described by Black (1908). This distinguishes five classes, as follows:

Class I. **Cavities in pits and fissures occurring on the occlusal surfaces of premolars and molars, the occlusal two thirds of the buccal and lingual surfaces of molars and the lingual of incisors.**

Class II. **Cavities occurring on the approximal surfaces of premolars and molars.**

Class III. **Cavities on the approximal surfaces of incisors and canines, not involving the incisal angle.**

Class IV. **Cavities on the approximal surfaces of incisors and canines in which the incisal angle is involved.**

Class V. **Cavities in the gingival third of the labial, buccal and lingual surfaces of all teeth.**

The above classification is used in much existing clinical and research literature, but it suffers from some limitations, not least the absence of any indication of size of cavity. This deficiency has recently been addressed by Mount and Ngo (2000). The classification used for GDS dental payments distinguishes, at least for amalgam fillings, between single surface and multiple surfaces, and MO (mesio-occlusal) or DO (disto-occlusal) and MOD (mesio-occluso-distal), another indication, at least for molars and pre-molars, of the extent of the cavity. The GDS classification will be used in the present work.

Having established the details of the tooth and the cavity, the next issue is the material used. Although in some other countries there is a move towards tooth-coloured restoration materials for all fillings (Mjör, 1997), the material of choice in the UK GDS is still dental amalgam, at least for back teeth (Sheldon and Treasure, 1999). The exact mixture of metals used may be expected to be relevant, but no distinction is drawn by the fee scale currently in use, so it is not possible to use DPB records to explore this issue directly. Although there have been many developments in tooth-coloured filling materials over the last decade, the classifications used in the GDS remain glass ionomer and composite resin. It is specified that these may not be used in load-bearing cavities in posterior teeth.

Remaining with the details of the original restoration, other associated treatment on the same tooth may be expected to be relevant. The presence of a root filling is an obvious example, and, if root fillings themselves are examined, a distinction could be anticipated between those root fillings in which the tooth is restored by an indirect restoration such as a crown or bridge and those which have a directly placed filling.

Also relevant to the individual restoration is the use of dentine pins or screws to improve the retention of the filling. The use of pin or screw retention may also indicate a particularly large cavity, where conventional means of retention by producing an undercut or parallel-sided cavity is not practicable without unacceptable weakening of the tooth structure.

The extent to which classifications of tooth cavities refer to the approximal surfaces (mesial and distal) is testimony to the importance of the adjacent teeth. The point of contact between adjacent teeth is a site for the onset of caries, and restoration work on neighbouring teeth may cause iatrogenic damage. It may be important to distinguish between work on adjacent teeth before, during and after the interval between the original filling and its replacement. Of particular interest will be work done in the same course of treatment as the filling or its replacement.

1.1.6 Dentist Factors

In the life of a restoration there is at least one dentist involved – the one who provided the original restoration. It is reasonable to suppose that the skill of this dentist may have some influence on how long the filling will last. The skill of a dentist results from a combination of undergraduate and postgraduate training, experience, and natural dexterity. Some, but by no means all, indicators of these may include the number of years since graduation, the dental school attended, the number of postgraduate courses attended, and the relative balance of different types of work carried out by the dentist in recent years.

Of at least as much importance as the dentist who placed the original filling is the dentist who elects whether or not to replace it. Treatment philosophy is important here, as is the interplay between patient and dentist. What one dentist will immediately elect to refill may be the subject of ‘wait and see’ from another (Bader and Shugars, 1992, 1995a and 1995b), and this decision may also depend on patient-related factors. The same considerations about dental skill apply to diagnosis as well as to the execution of treatment, and the same bank of indicators can be used. In principle, the same analysis applies to all intermediate dentists who have seen the patient and have elected not to intervene. However, this prompts consideration of an important subclass of restoration replacements – those where only one dentist has seen the patient throughout the whole time from original restoration to subsequent replacement.

1.1.7 Patient Factors

Patients also vary. Age, sex, and pattern of attendance may be correlated with longevity of restoration. They may be associated with different levels of expectation of treatment and co-operation with advice from dentists. Older patients are more likely to have greater numbers of existing restorations, they are likely to differ from others in dietary habits, and they have had a smaller proportion of their lives exposed to fluoridation, both of toothpaste and of water supplies. Females, at least until the oldest age groups, visit dentists more often (DPB, 1993) and may be more concerned about the aesthetics of treatment. They are also subject, within the GDS, to important exemptions from payment during and after pregnancy.

Pattern of attendance is an important factor, and it is compounded by censoring (section 1.1.4), in that it is difficult to distinguish between a patient who attends by choice only once every ten years and one who has left the NHS with no intention of returning. Regular attendees, so long as they stay with the NHS, are a particularly useful subclass, offering scope for matched comparisons of longevity for different teeth at different times. The other useful distinction is between patients who see two or more dentists over a period of time and those who remain with the same dentist throughout. It may also be useful to distinguish between patients who have changed dentists through choice and those who have simply responded to changes initiated by the dentists, such as movement between practices, retirement, and withdrawing, in whole or in part, from service in the GDS.

1.1.8 Location Factors

The location of the surgery, and of the patient's home, may be relevant for a variety of reasons. At a broad geographical level, the levels of fluoride in drinking water vary across England and Wales. Climate may also have a part to play. At a finer level, the postcode may be a proxy for other factors affecting dentist or patient, such as ambient levels of wealth or deprivation and diet.

More directly relevant may be the level of provision of primary dental services in the area – with consequential pressures to minimise or maximise the amount of treatment provided for each patient. The number of other dentists practising at the surgery address, and the pattern of prescribing of these other dentists, may be a useful indicator.

1.1.9 Economic Factors

It would be surprising if there were no relation between the fee paid by the patient and the patient's willingness to undergo treatment. The average cost of a GDS course of treatment where the patient pays no charge is considerably higher than for patients who are required to pay (DPB, 2002a). The cost to the NHS, which contributes only twenty per cent of the item of service gross fees for charge-payers (plus any excess over the maximum patient charge), is proportionally much higher for non-payers. It is therefore particularly interesting to know whether fillings last longer for charge-paying patients than for patients receiving free treatment.

By combining estimates of longevity with costs of treatment, it should be possible to express each treatment in terms of the long-term cost per tooth year. This is obviously important from a macro-economic point of view, although the individual patient might wish to take into account the frequency of replacement, or aesthetic considerations.

1.1.10 Aesthetic Factors

The external appearance of a filling has no bearing on its intrinsic longevity. Appearance may however influence the decision to replace it, either because the colouration of the filling or staining at the margin has changed over time or because what was previously acceptable is no longer considered so. Changes in the appearance of a filling may also encourage a dentist to suspect the presence of secondary caries, even when none is present.

1.1.11 GDS Factors

The conditions imposed for payment of dentists working under the regulations of the GDS restrict the range of treatments which can be provided on particular teeth. They also provide peculiar incentives to carry out particular treatments at particular time intervals, and to refrain from other interventions.

Here are a few examples. Consider first the routine check-up. The provisos to item 101 (Examination and Report) restrict the interval between two successive checkups to not less than five complete calendar months (Department of Health (2002)). The result is that six months, or thereabouts, has become the standard interval between successive courses of treatment, irrespective of the clinical needs of the patient.

One of the features of the ‘New Contract’ introduced in October 1990 is the ‘guaranteed replacement’. In the event of a restoration needing replacement within one year of its original provision, the dentist is entitled to replace it free of charge to the patient, and to claim the full payment from the NHS. This free replacement is restricted to replacing like with like, which discourages the dentist from using a different treatment, even though the evidence may suggest that the original choice may have been inappropriate. Free replacement is financially attractive in the case of charge-paying patients but not for those who do not have to pay patient charges.

The GDS regulations also stipulate that glass ionomer and composite resin restorations should not be used where the filling involves the occlusal surface of a molar or pre-molar tooth. In effect, this restricts such fillings to anterior teeth and the class V lesions of posterior teeth. This removes the choice from dentists, under the

GDS, but may encourage dentists to offer tooth-coloured restorations in load-bearing posterior teeth privately. Where this happens, there is, of course, no NHS record that the tooth has been treated privately.

The above examples are sufficient to demonstrate that the dentist's work in the GDS is not allowed the same clinical freedom as in the private sector, and that the pattern of treatment and attendance may not be simply the result of an informed consultation between dentist and patient.

1.1.12 Time Factors

All the above factors may vary over time, but generally in a gradual way. Over a period of a decade, there are, however, a relatively small number of significant events which might have a detectably significant effect on the longevity of restorations. The biggest events have probably been changes in the GDS rules. An example of these is the effect on the treatment of children – from 1990 to 1996, most fillings for patients aged under eighteen were funded by monthly capitation payments, and not separately recorded on claim forms sent to the Dental Practice Board. For this reason it is clearly inappropriate to analyse the intervals to re-intervention of patients under the age of eighteen across this period, but it is also possible that the changes had some knock-on effect on the resources devoted to the treatment of adult patients.

One theme which runs throughout the last decade of the twentieth century is the increasingly tight monitoring of registration records, and a consequent improvement in the reliability of data for tracking the records of a single patient between different dentists over time. This may have a technical effect on the reliability of conclusions drawn from different parts of the decade.

1.2 Objectives of this Research

1.2.1 Overview

Briefly, the objectives of this research are:

1. **To determine the longevity of direct-placement dental restorations provided within the General Dental Services in England and Wales, and,**
2. **To identify and quantify the factors affecting the longevity of direct-placement dental restorations provided within the General Dental Services in England and Wales.**

In the case of both objectives, the research was conducted through examination of the treatment activity records held by the DPB.

For the purpose of this work, the life of a restoration was considered to be the time interval between the date of completion of the course of treatment in which it was placed and the date of acceptance of the course of treatment when the next tooth-specific treatment was carried out on the same tooth.

To achieve these objectives, empirical distributions have been calculated, based on three different longitudinal samples drawn from DPB statistical records, concerning patients treated in the GDS during the eleven years ending December 31st 2001. Possible factors affecting longevity have been quantified and tested, and a model has been developed to explain and estimate past and future intervals between provision of directly placed restorations and the subsequent re-interventions on the same teeth. The samples consisted of

- a one-year follow-up of all the patients born in five reference years who had directly-placed restorations recorded during a particular calendar month,
- a cross-sectional study looking back one year on patients with re-interventions in a particular month, where the previous restoration had been a direct restoration within the previous year, and
- an eleven-year longitudinal dataset of all treatment received by a random sample of GDS patients, stratified by year of birth.

1.2.2 Empirical Distributions

The first part of the work involved the use of appropriate statistical methods, including Kaplan-Meier, to estimate survival curves for each of the three samples, exploring as appropriate the variation associated with the following covariates:

1. **Tooth position, individually and grouped by arch, quadrant and function (incisor, canine, premolar and molar)**
2. **Cavity type, as distinguished in the GDS Statement of Dental Remuneration**
3. **Material type – this is confounded with cavity type above.**
4. **Additional treatment on same tooth – root filling and pin or screw retention**
5. **Those with and without other treatment at the same time as the first restoration.**
6. **Age, sex and experience of dentist providing original restoration.**
7. **Country of qualification of dentist providing the original restoration.**
8. **Age and sex of patient at time of acceptance for the course of treatment in which the original filling was placed.**
9. **Patient attendance pattern, determined by the median attendance interval, mean annual gross fees, and the number of different surgeries or dentists attended.**
10. **Geographical area of surgery - and hence the water fluoridation level in the area.**
11. **Charge-paying status of patient at both dates of acceptance (initial restoration and re-intervention).**
12. **Other covariates, including the year and month of placement, as appropriate.**

1.2.3 Selection of Covariates

In the light of the findings of section 1.2.2, a set of quantified factors which appeared to have a significant relationship with longevity of restorations was extracted and documented.

1.2.4 Statistical Models

After examination of the results in sections 1.2.2 and 1.2.3, including the similarity of the shapes of the survival curves for different subgroups of the population of restorations, a fully parametric statistical model was developed, using the Cox Regression semi-parametric method to describe the underlying structure of the data and the relationship between the survival curves of different subgroups of restorations, and curve-fitting techniques to characterise the underlying baseline survival curve.

1.2.5 Robustness

The eleven year analysis was carried out on a sample consisting of all treatment records for treatment provided to all patients whose birthdays are on a particular randomly chosen list, such that one birthday falls in each calendar year. The sample was restricted to adults, aged 18 years or over on the date of acceptance for treatment.

The models generated by section 1.2.4 were then tested on a second sample, chosen in the same way, but using different dates.

1.3 Data Sources and Structure

1.3.1 The General Dental Services

The General Dental Services for England and Wales (GDS) have existed since 1948, having been set up under the 1946 National Health Service Act. Much of the system of regulation and remuneration can be traced back further to the regime of the 'Approved Societies' recognised under the 1911 National Insurance Act.

The GDS account for the majority of the primary dental care provided within the NHS. Other players include the Hospital Dental Service (HDS), particularly the service associated with training students of dentistry, the Community Dental Service (CDS), which concentrates on patients who have special needs which may be inappropriately catered for by the general dental practitioner, and the Personal Dental Services (PDS), introduced in 1998, which consist of a wide range of small pilot schemes providing an alternative to the GDS. The PDS include the 'Dental Access Centres' - a service targeted at patients who would not otherwise be expected to gain access to NHS primary dental care.

The GDS are administered in England and Wales by the Dental Practice Board. In Scotland and Northern Ireland there are similar bodies - the Scottish Dental Division in Scotland and the Central Services Agency (CSA) in Northern Ireland.

The essential feature of the General Dental Services is that General Dental Practitioners (GDPs) are independent contractors, free to set up their dental business wherever they choose, and paid by item of service rather than salary. There are two other minor areas of the GDS, paid for out of the GDS budget but not included in the source data for this research study, which are worth mentioning. They consist of the Salaried Dental Service (SDS) and the Emergency Dental Service (EDS). Both these services are provided by local Health Authorities subject to approval by the Department of Health. In each case, the Health Authority receives a budget from the Department to employ dentists to deal with specific local problems. In the case of SDS dentists, the practitioner is generally employed on a long-term basis, and usually has no other GDS contracts. EDS dentists, by contrast, are usually GDS contractors who provide EDS work on a sessional basis. Not all health authorities have SDS or EDS dentists, and those that do do not necessarily require their SDS or EDS dentists to report their work to the DPB.

Work in the GDS is governed by two main documents: the Statement of Dental Remuneration (SDR) and the GDS Regulations. These are regularly up-dated, the SDR sometimes several times in one year. They set out the terms and conditions under which GDS dentists are required to provide a service, and include the fees payable and the detailed provisos setting out the conditions under which particular treatments and combinations of treatment may be claimed.

In order to practise in the GDS, a dentist must provide details of his registration with the General Dental Council (GDC), together with the address at which he intends to practise and details of his association with other dentists practising in the GDS. A particular feature of these associations is that it is possible for a dentist to take responsibility for a course of treatment undertaken by an assistant or trainee dentist in his or her employment. It is reasonable to suppose that the there may be some differences between treatment done by the principal dentist and that done by his or her assistant. The DPB records enable most of such cases to be identified, though there is always the possibility that some short-term locum activity has not been recorded.

1.3.2 Dental Practice Board

The Dental Practice Board (DPB) is the statutory body charged with processing payment claims from GDS dentists, assuring the probity of those claims, and providing NHS managers with information about the activity in the GDS. The DPB's duties and powers are enshrined in various parliamentary acts and regulations, dating back to its foundation, as the Dental Estimates Board, in 1948.

The GDS regulations, which the DPB administers, have undergone many changes over the last fifty years. Arguably the biggest came in October 1990, when the so-called 'New Contract' was introduced. Prior to then, all GDS patient treatment activity had been paid for entirely by item of service fees – calculated by reference to a standard price list. The 1990 changes involved the introduction of monthly capitation and continuing care payments in respect of all patients on a dentist's 'list'. The activity funded by these monthly payments differed between adults and children, with much child activity, including the placing of fillings, included within capitation payments, while adult continuing care payments were in addition to the existing item of service fees.

One beneficial consequence of the 1990 reforms was that the DPB developed sophisticated techniques for accurately capturing patient identification details, in order to minimize the extent to which two dentists could simultaneously be paid for having the same patient on their lists. These techniques were developed and introduced over a period of years, starting in early 1991, so that the proportion of errors in the earlier data is likely to be higher than in the later.

Other changes introduced in 1990 include a reorganisation and redefinition of the item of service codes relating to fillings. From 1990 most filling items refer to the number of teeth treated, rather than the number of fillings placed.

Three other 1990 changes may have had a bearing on the incidence of filling treatments under the GDS. The first is the introduction of ‘Prior Approval by Volume’. This required dentists to refrain from carrying out courses of treatment for which the total fees were likely to exceed a certain threshold, unless they had previously sought, and received, permission from the DPB. The threshold was originally set at £500, then raised to £600, before being dramatically reduced to £200 in 1992.

The second of these three changes was the allowing of mixing of NHS and private treatment within the same course of treatment, though not on the same tooth. This may distort the picture of follow-up treatment, since the dentist is not obliged to record what private treatment has been provided – though since 1997 there has been a requirement on dentists to report whether any private treatment has been provided during the GDS course of treatment.

Thirdly, dentists were obliged to provide to their patients a written treatment plan, detailing the proposed work, the anticipated patient charges, and which of the treatment items, if any, were to be provided privately (and at what price). Whether or not this obligation was universally discharged in full, it represents a significant step towards involving the patient in the treatment planning decision, and may therefore have had some impact on the pattern of treatment provided.

Over the next decade there were many lesser changes to the GDS, and to the DPB's role in administering both the regulations and the consequential activity. In 1990 the DPB had taken on the full role of providing the Dental Reference Service, an inspection function involving the arrangement of re-examination of GDS patients by a DPB team of 'Dental Reference Officers'. These are experienced dentists employed by the DPB to give a second opinion on the quality of diagnosis (in the case of prior approval requests) or of treatment, where patients have been chosen, by a combination of random and targeted methods, after a claim for payment (after completion of treatment) or a request for prior approval has been received from a dentist. In 1991 the DPB became responsible for making direct payments of all fees to dentists, after adjusting for pension contributions, National Insurance, and other items such as postgraduate training allowances, rather than simply providing a schedule of payments due.

1.3.3 The Patient Treatment Data

When the New Contract was introduced, the opportunity was taken to review the systems used to provide information about treatment activity within the GDS. Prior to 1990, detailed treatment activity statistics had been provided by aggregation of a systematic sample of treatment records, according to a pre-specified set of aggregation tables. The detailed records themselves were not retained.

Starting in 1990, this system was replaced by a combination of 100% aggregate tables and a detailed sample consisting of all the treatment records relating to all patients whose dates of birth matched a randomly chosen set of birth dates. This latter sample has been retained in its full detail, and is known, for reasons which will become obvious, as the DPB's longitudinal treatment sample.

The longitudinal sample data also contain equivalent records showing the treatment code which would have been used if the treatment had been provided under the scale current at the end of the month in which it was (nominally) processed. These converted records were of considerable value for coping with old claims during the first few months of the New Contract, but are not generally be necessary for claims with dates of acceptance after October 1990.

There are also statistical records, identifying the incidence of different treatment fees, and in particular those associated with provisos in the SDR. The statistical records are used primarily for producing the detailed aggregate treatment statistics in the DPB's Annual Digest of Statistics (DPB, 2002b), but they could also be used for summarizing the other treatment which a patient receives, in addition to the specific restorations which are the subject of this research.

For the years since October 1997, a full set of data, not restricted to a sample, is available, and this can be used for more detailed examination of short-term rates of re-intervention. This full set of data does not however contain the converted or statistical records which may be found in the longitudinal sample data.

1.3.4 Supplementary Dentist Data

In addition to the detailed treatment data held at the level of individual patients, the DPB has compiled hundreds of monthly totals of activity counts at the level of individual dentists, and further subdivided into their separate contracts with health authorities. The total numbers of teeth filled and root filled may be particularly relevant to this work.

Information is also held on the history of dentists, including the year and country of qualification, their sex and date of birth. Certain specific subclasses of dentist – vocational dental practitioners (previously known as vocational trainees) and assistants for example – can be identified from contract records, as can the dentist's pattern of moving between surgery postcodes and the number of different dentists practising at any particular surgery postcode.

From the additions and deductions forming the final part of the payment process it is also possible to gain a statistical measure of the extent to which a given dentist is engaging formally in postgraduate training.

1.3.5 Other Sources

By using surgery postcode, links can be made to other published data, such as fluoridation levels. The UK Department for the Environment, Food and Rural Affairs is a good source for geographical information about the levels of natural and artificially added fluoride in drinking water.

2 LITERATURE REVIEW

2.1 Introduction

2.1.1 Sources

In reviewing the literature for this subject, any source material with a clear relevance has been included, without prejudging its merits against any presumed hierarchy of evidence. The primary source consisted of the papers accumulated over several years by one of the supervisors, and this was subsequently supplemented by a MedLine search, plus some references derived from statistical work and recently published papers.

2.1.2 Related Topics

In addition to the literature specifically concerned with the longevity of directly placed restorations, useful material was also found on the quantification of the lives of other dental treatments, including crowns, bridges and inlays. An important related area concerns the range of possible reasons for re-intervention, and in particular, the definition and diagnosis of secondary caries. In this chapter the related topics and issues of definition and methodology are covered first, followed in section 2.6 by the main quantitative results to be found in the literature.

2.2 Review Papers

2.2.1 Reviews of Longevity

Several relevant reviews have been written in recent years. The most comprehensive of these are those by Jokstad et al (2001) and Manhart and

Hickel (2001). Other recent reviews include those by Downer et al (1999), Jones et al (2000), Randall and Wilson (1999b), Hickel and Manhart (2001), Manhart et al (2002) (a later version of Hickel et al, 2000), Hickel and Folwaczny (2001), and Van Dijken (2003), though some of these deal with a narrower subclass of direct restorations. Blatz (2002) provided a comparative literature review of longevity of all-ceramic posterior restorations, contrasting them with amalgam, resin composite, cast gold, and porcelain-fused-to-metal (PFM). Phillips et al (2000) considered longevity in the context of the economics of providing dental treatment, while Jedynakiewicz and Martin (2001) also considered the current philosophy of dental intervention, and the growing emphasis on evidence-based dentistry.

The early review literature on the life of restorations derives mainly from the work of Elderton (1976a, 1976b, 1977, and 1983a), followed by Robbins and Summit (1988). The latter was more than a review paper, but contains a useful overview of the early literature. In the last decade, the mantle has been taken on particularly by Mjör and associated workers - Mjör (1989), Mjör et al (1990), Jokstad and Mjör (1991a), and Kidd et al (1992). Bader and Shugars (1992, 1995a and 1995b) considered the literature on longevity within the wider context of variation in decision-making and treatment outcomes.

The use of systematic reviews and meta-analyses, including or excluding papers according to a preset list of criteria, has also been the subject of some discussion. Examples may be found in Chadwick et al (2001a), Treasure et al (2000), Dunstan et al (2000), and El-Mowafy et al (1994)). Sheldon and Treasure (1999) translated the results of a systematic review into policy implications, but recognised the gap between the ideal conditions to which they restricted their included studies and what happened in practice.

Chadwick et al (2001a) considered the difficulties in a systematic review of combining evidence from existing literature on dental restoration longevity. From a preliminary search return of over 14,000 scientific articles, barely one hundred contained sufficient core information and had acceptable methodology to merit inclusion. They concluded that the two most common types of study within those considered to be acceptable were a) strong experimental design over a short period in an institution, and b) weaker design over a longer period in a primary setting. The ideal would be a long-term, multi-operator, controlled clinical trial in a primary care setting.

2.2.2 Reviews of Related Subjects

In addition to reviews of longevity of directly placed restorations, there are several review papers covering related topics. In particular, Bader and Shugars (1992, 1995a and 1995b) provided a good overview of the literature concerning the clinical decision to intervene on a tooth, whether or not it has previously been restored. Eriksen (1980) considered methods of measuring the state of a restoration. More details of this work can be found in section 2.4.3.

Fontana (1993) and Mjör and Toffenetti (2000) considered secondary caries, and the criteria used to diagnose it. Randall and Wilson (1999a) also considered the evidence for an inhibiting effect on secondary caries arising from the use of glass ionomer. Their review is typical of many, in that they found that no papers met the original inclusion criteria, and they had to relax their criteria in order to have anything to report. Their conclusion was that there was no conclusive, overall, evidence for or against a cariostatic treatment effect for glass-ionomer restoratives.

Cervical lesions have a literature of their own, including the debate about stress-induced non-carious cervical lesions, which have been described as ‘abfractions’ (Rees, 2000). Relevant reviews can also be found in Lee and Eakle (1996) and Blunck (2001).

Finally, two reviews on the longevity of indirect restorations have provided a context against which to compare the work on direct restorations. Dummer et al (2000) considered porcelain & composite inlays, with a maximum follow-up time of five years. Most cases were from prospective studies (66% of restorations). The rest were from randomised controlled trials (19%) or other clinical trials (15%).

Brochu and El-Mowafy (2002) considered the longevity literature concerning a particular type of indirect restoration (IPS-Empress). All the studies were short-term ideal-conditions clinical trials, generally using United States Public Health Service (USPHS) classification or similar criteria for assessing clinical performance. The paper recommended that patients should be informed of the likely future rate of failure for such restorations, and also noted that the lack of evidence from long-term clinical trials precluded recommendation of this type of restoration for posterior restoration.

2.3 Reasons for Failure or Replacement

2.3.1 Introduction

Fundamental to any study of the variation in longevity is an understanding of reasons which are given for asserting that a restoration has come to the end of its life.

There is extensive literature on the reasons why a dentist should place or replace a restoration. Most studies have shown that more than half the direct restorations placed in adults are actually replacements of previous restorations (Jedynakiewicz and Martin, 2001 and Boyd and Richardson, 1985). In the last two decades estimates of the proportion of direct restorations which are replacements as opposed to initial placements range from 49.4% (Friedl et al, 1995 – Germany adults and children), through 51% (Burke et al, 1999 – UK adults and children), 60% (Wilson et al, 1997 – UK adults and children), 66% (Burke et al, 2001 – Scotland adults and children), 71% (Maryniuk and Kaplan, 1986 – USA adults and children), to 73.8% (Mjör, 1981 – Norway adults and children). Deligeorgi et al (2001) quoted ten different studies illustrating the range of proportions of replacement restorations according to country. There is considerable variation between countries in the ratio of initial to replacement restorations, with Scandinavia, UK and USA having the lowest rates, and Italy, Greece and South Korea at the other extreme.

Mjör (1989) used several other Scandinavian sources to illustrate the balance between placement and replacement, distinguishing between children (under age 16) in primary dentition, with about 48% replacement, children in permanent dentition, with about 20% replacement, and adults (16 and over) at around 70% replacement.

Boyd (1989) took the discussion a stage further back, ascribing the main causes of failure of a restoration to at least one of three factors: the dentist, the materials, and the patient. This paper is concerned with the training of dentists, and in particular traditional training slanted towards practice in restoring rather than in decision-making. Improved oral health has led to a dearth of suitable patients for training in decision-making, and hence an emphasis on restoration. 'Repair' rather than restoration by replacement was frowned upon in training. Boyd also considered other factors such as financial rewards which encourage replacement rather than 'watching'.

Several studies have sought to quantify the proportion of different reasons for placement or replacement of restorations. Elderton and Nuttall (1983), followed by Elderton (1983a) considered the treatment proposed by seven GDPs and eight hospital dentists for eighteen young adult patients, assuming they would next attend routinely after six months. Out of 1,145 restorative decisions proposed, almost 59% were agreed to by less than half of the group of dentists. Davies (1984) conducted a five year follow-up study of 116 patients from the 1978 Adult Dental Health Survey of Scotland. She found that those who changed dentist received more of every type of treatment, particularly restorations. Morgano et al (1994) concluded that there is significant variation in both philosophy and techniques used by location of dental practice, by type of dentist and, in some respects, by age of dentist. Bader and Shugars (1992 and 1995a and 1995b) drew on a wide literature review to show that variation in diagnosis and treatment planning was ubiquitous.

Mjör (1981) reported on a Norwegian study of 5,487 restorations placed by 85 private practitioners in two two-week periods in 1978 and 1979. Most (73.8%) were replacements of existing restorations. Secondary caries was the main reason for replacing amalgam restorations (58% of the 74% which were amalgam). For tooth-coloured restorations (mostly composite resin) the main reason (40%) was poor anatomical form, followed by secondary caries (20%) and discoloration (20%).

Mjör and Qvist (1997) conducted an analysis of self-selected reports from 550 dentist participants on a specialist course on resin-based composite restorations. The reports covered 235 amalgam and 193 composite restorations. Secondary caries was the most common reason given for the replacement of restorations. This study shows a good correlation between the clinical diagnosis of secondary caries in the form of a (visible) outer lesion, and the presence of a wall lesion. Secondary caries was most commonly found in the gingival portion of the restoration. Where the pre-operative diagnosis was marginal defects only, caries was rarely discovered on the cavity walls or floor, but when it was, it was more frequently found to be associated with amalgam rather than composite restorations.

Although caries is, overall, the most common reason given for placement and replacement of restorations, York and Arthur (1993) found that as patients got older, more restorations were placed because of non-carious reasons, such as fracture and endodontic treatment, and fewer because of caries. For patients aged 35 and over such non-carious reasons were more common as reasons for placement than caries. Friedl et al (1994 and 1995) reported on a cross-sectional study of 3,375 composite resin fillings placed by 102 dentists practising in southern Germany. Secondary caries was the reason for replacement in 40% of replacements - the largest single reason. The exception was four-surface restorations, where fracture was most frequent reason. Mjör and Moorhead (1998) considered reports from 27 clinicians in Florida on restorative materials, reasons for replacement, and age of restorations replaced. The main reason for replacement was secondary caries (56% for amalgam and 59% for composite) followed by fracture and discoloration.

More confirmation of the balance of reasons for replacement is given by Mjör et al (2000). This is another Norwegian study, covering the reasons reported by dentists for the replacement of 9,805 amalgam, composite, glass ionomer and other restorations. Across all subgroups of the population, secondary caries was the main reason given for replacement, followed by fracture of restoration, generally bulk fracture. Discoloration, also generally bulk, was the next most frequent reason given for composite restoration replacements.

2.3.2 Secondary Caries

Chief among the reasons given for replacement or other re-intervention on a previously restored tooth is a diagnosis of secondary caries. Definition and diagnosis of this condition is however problematic.

In an *in vitro* study by Merrett and Elderton (1984), nine dentists at Dundee Dental Hospital were presented with the same set of 228 extracted teeth, fixed in plasticine in a simulated clinical setting. The dentists were asked to assess a specific region of each tooth and indicate whether they thought the region was carious, and whether they would extract, restore, grind/polish, or leave untreated. The teeth were then sectioned and examined with a stereoscopic microscope and an expert opinion (based on two clinicians) given on whether there was caries present.

There was dramatic variation between the nine dentists. The number of teeth considered to need treatment ranged from 28 to 119, and there was widespread disagreement on which teeth needed restoration - only 17 out of 145 proposed for restoration had unanimous agreement.

Not only was there little agreement between the dentists on the presence or absence of caries, there was little relation between any of their assessments and those obtained after sectioning. Further, many of the teeth proposed for treatment were so proposed by dentists who did not think there was secondary caries present - implying an 'if in doubt, treat' philosophy.

Foster (1994) conducted a study of 80 dental school patients who were diagnosed as needing replacement of a defective amalgam restoration. Of these, 51% were judged to have secondary caries. The findings were checked against the state of the underlying dentine. Soft dentine (carious) was found in 88% of those judged to have secondary caries, but hard dentine was found in only 49% of those teeth which were diagnosed as non-carious. The conclusion was that dentists were quite good at identifying cases where there was caries, but quite bad at identifying cases where there was none.

Kay et al (1995) considered the utility of dentists' decisions based on bitewing radiographs. Twenty GDPs decided whether or not to restore, given each of fifteen pairs of simulated bitewing radiographs. For 6,190 out of 7,200 decisions the actual depth of lesions was determined by microscopic section, and likely prognosis based on a literature search of longitudinal studies of lesion progression and restoration failure. Probabilities of satisfactory and unsatisfactory outcomes were multiplied by patient utilities determined by standard gamble questionnaires administered to 110 members of the public. The authors concluded that, given the utilities of the patient, the maximum expected utility was generally achieved by not treating. The only exception occurred with patients who had a recent history of decay in previously sound teeth.

Three microbiological studies revealed the somewhat tenuous relationship between clinical indicators and the underlying microbiological status of teeth. Kidd and O'Hara (1990) conducted a histological study of thirty extracted teeth with occlusal amalgam fillings, sectioned to compare ditched and clinically sound areas of the same tooth. The teeth were examined with a stereomicroscope, and photographed at 6x magnification. Caries was then measured by hand-grinding and examination using polarised light. The relationship between the presence of caries and ditched or intact margins was tested using a sign test and found not to be significant.

Kidd et al (1995) examined 330 microbiological samples drawn from 175 amalgam-restored teeth of 118 patients. Patients were volunteers at UMDS, Guys. Sites were classified by the following clinical indicators:

1. Marginal ditching: <0.4mm, >0.4mm, intact, and frankly carious
2. State of dentine: hard or soft
3. Marginal discoloration: presence or absence of staining

These were compared with Mutans Streptococci and Lactobacilli counts, measured as log10(cfu per sample+1) and as a percentage of total colony count. Comparisons were made using t-test for dichotomous data and for paired samples, and one-way analysis of variance for data with more than two categories, with means compared by Duncan's multiple range test. All analysis was done using SPSS.

They concluded that:

1. **Frank carious lesions should be restored.**
2. **A slight ditch should not trigger replacement.**
3. **It might be prudent to replace restorations with gaps > 0.4mm.**
4. **Colour change alone should not trigger replacement.**

Further work refined these conclusions. Kidd and Beighton (1996) conducted a similar microbiological study of plaque samples from 197 sites on 113 teeth with tooth-coloured restorations, from 73 patients attending UMDS (Guys). They used the same methodology, finding that, apart from frankly carious lesions, no clinical indicators were reliable predictors of underlying active caries. Soft dentin was a good indicator, but could not be examined without removing the restoration first. The presence of staining was statistically significant as an indicator of caries (by contrast with amalgam restorations), but not sufficiently reliable for clinical use.

Mjör (1998) asked a group of clinicians to record the location - gingival, occlusal/incisal, other - of their diagnoses of secondary caries. Over a thousand cases were recorded, spread across different types of cavity and different restoration materials. In all cases the overwhelming majority (over 75%) were in gingival locations. This is not surprising, since at such locations it is more difficult to remove plaque. It is also an area of greater uncertainty for diagnosis, since the dentist generally has to rely on whether an explorer catches, rather than direct observation. Because of this uncertainty, Mjör suggested that experimental patching might prove clinically more effective than routinely replacing the whole restoration.

2.3.3 Other Reasons

After secondary caries, bulk or marginal fracture and, in the case of tooth-coloured restorations, deterioration in colour match, are the main remaining reasons for replacing restorations. Bulk fracture, together with the associated pain, discomfort, or aesthetic considerations, is perhaps the only diagnosis which is so directly perceptible by the patient as to prompt an unplanned visit to the dentist. Most other reasons rely mainly on an assessment by the dentist as to the presence, extent and significance of the condition.

Heinikainen et al (2002) conducted a study of treatment philosophies by postal questionnaire. A sample of 400 Finnish GDPs, stratified by age (30-39 and 40-

49), sex and sector (public or private) was chosen, plus 47 dental teachers. All were presented with the same set of hypothetical cases of failed restorations, and asked to choose from a range of treatment options without economic constraints. The conclusions were that there was general agreement on composite restorations for the smallest cavity, and indirect restoration for the largest, but there was considerable disagreement on intermediate cases, with private dentists tending to prefer indirect restorations.

Wilson et al (2003) reported on a self-selected sample of 92 Denplan dentists (out of 700 approached) in the Midlands and north-west of England. These dentists reported on the tooth position and reason for placement or replacement of each crown provided over a twelve-week period between March and July 1998. The tooth positions for which initially placed crowns were most frequent were upper premolars, lower molars and upper incisors. By contrast, more than half of the replacement crowns (441 out of 712, 62%) were on upper incisors. The most common reasons given for initial placement of crowns were tooth fracture and (direct) restoration failure, followed by aesthetics, while, for replacements, the reasons were restoration failure (that is, previous crown failed), aesthetics, secondary caries and unacceptable marginal adaptation.

Going and Jendresen (1972) provided advice to practising dentists on how to restore teeth well. They set out all the issues which may affect the subsequent performance of restoration materials. Harrison (1972) provided a technical discussion of failures of restorations resulting from errors in prevention, diagnosis, treatment planning, restorative therapy and post-operative care.

This article was confined to replacement of teeth, by dentures and bridges, and cast restorations. There was no coverage of 'normal' failure resulting from restorations wearing out, including failure of materials.

Other papers, particularly on the reasons for extraction of teeth, give further insight into why a restored tooth may require re-intervention. Kay and Blinkhorn (1986) conducted a questionnaire-based study of reasons for extracting teeth. A sample of 25% of the 1,327 Scottish GDPs was chosen, and 63% responded. Each reported on one week's extractions - a total of 2,190 teeth. Overall, 50% were removed because of caries, 21% for periodontal reasons, 12% pre-prosthodontic, 5% at patient's request, 3% for trauma, and 1% for other reasons. Dental attendance pattern was important. Regular attendees (ie those who attended in last two years for a check-up) had fewer extractions (41%) than irregular (59%), but the paper did not state the number of different patients from whom the 2,190 teeth were extracted. Caries accounted for 61% of teeth extracted from irregular attendees, while regular attendees had only 36%. It is possible that the reasons for extractions may have changed in the seventeen years since this study was published, though Kay and Blinkhorn’s figures remain broadly consistent with the following more recent studies.

A similar study was carried out by Agerholm and Sidi (1988). They drew a random sample of GDPs from England and Wales - 500 were chosen, of whom 250 originally accepted, then 30 withdrew. Of the remainder, 31 did no extractions in the survey month. The remainder generated 5274 extracted teeth from 2912 patients. Overall, reasons given were caries (48%), periodontal (27%), orthodontic (13%), eruption problems (5%), and pre-prosthetic (4%).

For patients aged up to 20, orthodontic reasons were prevalent. From 21 to 60, caries was the most common reason, though declining with age. From age 61 onwards, periodontal reasons predominated. Agerholm and Sidi compared their results with those for Scotland, where the extraction rate was greater. They also noted that the pool of available teeth got smaller as patients got older.

Hull et al (1997) examined extracted teeth for 192 male and 197 female patients from 21 Manchester and Salford dentists. Details of patient's age, sex and attendance pattern (regular attendee defined as one who had attended within previous twelve months) were recorded. Sixty-eight per cent were regular attendees. The main reason for extraction was caries (37%), followed by periodontal disease (29%). Over age 50, periodontal disease was a more frequent reason than caries. They concluded that the reason given for extraction was consistent with the examiners' findings - more caries when caries was given as the reason, more periodontal disease (measured as attachment loss) when this was given as the reason.

Randall et al (2003) reported on a questionnaire-based survey of 1,217 group practice principals, out of 2,800 approached, concerning attitudes to a bank of twenty statements about the future of primary dentistry. The statements had been prepared using the Delphi technique with a panel of nine dental experts. For each statement, respondents were asked to rate it on scales of importance, confidence, desirability, feasibility and probability. Where 70% of the dentists agreed in their ratings the statement was elevated to the status of 'indicating a possible trend in aspects of the clinical practice of restorative dentistry in the UK'. The most highly rated statement was 'root caries lesions are increasingly seen in elderly patients'.

2.3.4 Cervical Lesions

Cervical lesions – Class V in Black's 1908 classification of cavities (Black (1908)) – have been subject to considerable debate as to how they are formed and what is the most appropriate treatment. Three review papers on the subject have already been mentioned (section 2.2.2).

A study was carried out by Folwaczny et al (2001), involving comparison of composite, polyacid-modified resin composite, and two resin-modified glass ionomers on the patients of one dentist. A total of 197 cervical restorations were placed on 37 patients, with treatments randomised across the four types of material. Only 130 restorations were available for follow-up after three years. The remainder had either been replaced by other restorations (eg crowns), or extracted, or the patient was no longer contactable. Eleven of the 130 restorations had fallen out, but a log-rank comparison of Kaplan-Meier survival curves did not show a significant difference in longevity between the materials.

The remaining 119 restorations were clinically evaluated using modified USPHS criteria. The composite restorations performed best, and the resin-modified glass ionomers worst, particularly on surface texture and anatomical contours. The paper discussed the possible explanations in terms of the particle size and physical properties of the different materials.

Pintado et al (2000) conducted a detailed study of three teeth (lower left pre-molars and first molar) of one adult measured on three occasions over a fourteen year period. The subject had excellent periodontal health and oral hygiene and had no restorations, lived in a fluoridated area and brushed teeth regularly with an electric toothbrush. The three teeth all developed non-carious lesions, which were measured by volume, using a digitiser to measure from stone models of the mandibular arch. Each tooth digitisation involved about 25,000 points.

The theory of abfractions suggests that the amount of tooth loss in a stress-induced non-carious lesion should be proportional to the occlusal work performed, which in turn should be proportional to occlusal wear. Occlusal wear was measured by volume in the same way as for cervical lesions, and a scattergram was drawn of the nine observed points, which were indeed highly correlated.

Other papers considering the merits of different materials for restoring stress-induced cervical lesions include those by Tyas and Burrow (2002) and Di Lenarda et al (2000).

2.4 Definitions of Life of Restoration

Depending on the type of study and the data available, there are several different ways in which the ‘life’ of a restoration can be measured. They range from the *de facto* consequences of a clinician's decision to re-intervene on the tooth, through assessments made by an, in some sense, independent assessor, to strict measurements taken in either a clinical or laboratory environment.

2.4.1 Administrative Rules

At its simplest, an administrative rule measures the life of a restoration from the date of placement to the date of next intervention. Robinson (1971) produced a clinically based set of rules for determining whether to ascribe a re-intervention to a failure of the original restoration. His rules were based on a 21 year longitudinal study of 43 regular patients attending one London suburban practice from 1948/9 to 1969. For example, a second single surface occlusal amalgam on a molar tooth was assumed not to be a replacement of the original. His 'Robinson correction' set of rules for deciding whether a new restoration was a replacement of a previous one has been used in other studies (such as Crabb, 1981 and Drake, 1988). Elderton (1983b) adopted Robinson's rules, together with a range of empirically based assumptions for matching teeth and patients between a sample of 720 dentate adult ADHS (Adult Dental Health Survey) records and subsequent SDD (Scottish Dental Division) records.

Many authors have confined their attention to replacement restorations, treating other re-interventions as censored, or ignoring them altogether. Smales et al (1991a) drew a distinction between 'true' and 'apparent' failures - 47 out of 444 (10.6%) were 'apparent' - eg unrelated extractions, endodontic, incorporated into other restorations, or trauma damage. Smales and

Hawthorne (1997) drew a similar distinction and regarded endodontic treatment, periodontal extractions, and bridge retainers as censored.

Martin and Bader (1997) explored the variety of outcomes over a five-year period on complex (four or five surfaces) posterior amalgams, and compared them with gold and porcelain crowns. The patients were adults with five years continuous membership of an American dental insurance scheme, and they were treated in a routine context by a total of 74 different dentists.

Out of 7,687 such restorations originally placed, a total of 4,735 were tracked for the full five years. Successful survival was defined as needing no further treatment or only an additional one or two surface restoration. On this basis five year survival rates were 72% for four surface amalgams, 65% for five-surface amalgams, and 84% for both gold and porcelain crowns.

In the study which bears the closest similarity to the present one, Bogacki et al (2002) used a claims-based data warehouse with longitudinal data since 1993. The whole patient data base of the Washington Dental Service (WDS) was approximately 1.5 million patients, from which just over 300,000 were selected for the study. This study covered posterior multi-surface direct restorations, and contrasted amalgam and composite. A restoration was defined as failed if it was replaced by another restoration with the same tooth surfaces. Restorations were treated as censored if they received no more treatment up to the end of follow-up, or if the tooth received a larger restoration, crown, or endodontic treatment, or if the tooth was extracted.

A total of 300,753 patients were included in the study, but each patient contributed only one multi-surface posterior restoration 'in order to maintain independent data'. Cox regression, using SAS, was used to test the associations of restoration longevity with the following predictor variables: patient gender, age, dentist age, tooth location, prior restorative history (number of restorations in year prior to restoration), year of treatment, change of dentist (defined as change of dentist between index restoration and replacement), and restoration material type. A log cumulative hazard plot was used to check the proportional hazards assumption. All predictor variables other than patient sex were statistically significant. Dates of provision were rounded to year, and Kaplan-Meier charts drawn. The main purpose of the Bogacki et al (2002) study was to show whether posterior amalgams still outlived posterior composites. This was demonstrated, although the observed difference was quite small, compared with other factors such as change of dentist - which was encouraged by the rules of the WDS.

The paper also gives a useful table showing the year by year change in the balance between amalgam and composite restorations.

2.4.2 Assessor Rules

When the volume of data was limited, several researchers attempted to standardise the measurement of the ‘end’ of a restoration life by using calibrated assessors, working to a standard set of rules. There are two main sets of rules in use, both deriving originally from the work of Ryge (1980). The system consists of a series of yes/no clinical questions, on the basis of which clinically (as opposed to statistically) significant classifications into Alpha, Bravo, Charlie and (sometimes) Delta can be made. This system is the basis for the USPHS (United States Public Health Service) classification, and also the CDA (California Dental Association) rating system - a more detailed development of it.

An important part of the system, not always followed in subsequent research, is a set of rules requiring two different dentists to make independent evaluations, and specifying how disagreements are to be resolved. A comprehensive description of both the USPHS and CDA criteria can be found in Jokstad et al (2001).

Ryge criteria and variations on them have become standard practice in clinically based research. Examples may be found in the following papers: El-Mowafy et al (1994), van Dijken (1996), Strand et al (2000), Geurtsen and Schoeler (1997), Crisp and Burke (2000), Wilson et al (2002), Van Dijken (2003), Jokstad and Mjör (1991a) and Mörmann and Krejci (1992). The last of these papers actually covers a survival study of adhesive ceramic inlays, but it is a good example of the methodology.

Wucher et al (2002) described a split-mouth three year trial of three different tooth-coloured restoration systems. All three (compomer, composite, and compomer/composite sandwich) performed well over the three year period, with only one failure (ascribed to root caries) among the twenty surviving patients out of the twenty-three who originally participated (three were lost to follow-up). The restorations were examined using modified USPHS criteria. This showed that Dyract (the compomer) sometimes formed a slight step, at restoration margins, which could be detected with a probe. The other difference detected was significantly greater wear, measured as 'bravo' for anatomical form, for Dyract.

2.4.3 Measurement Rules

As an alternative or adjunct to assessments by clinicians, several techniques have been developed to measure the change in restoration characteristics. These techniques are particularly suitable for early assessment of new materials.

Eriksen (1980) considered the relative merits of indirect and direct methods of evaluating the performance of fillings, and in particular composite resin restorations. For clinical survey purposes direct evaluation, using for example the Ryge system, was most suitable. For controlled experiments, indirect methods had advantages, such as the opportunity for precise measurements, longitudinal comparisons and double blind evaluation.

Examples given included the use of a scanning electron microscope and other equipment to measure marginal integrity, occlusal wear, and surface roughness on replicas, laboratory analyses of intra-oral samples (eg for caries), and clinical photography for both marginal and general discoloration. However, some indirect methods may not have been suitable for inaccessible areas such as inter-proximal surfaces.

Randall and Wilson (1999b) considered the history of dental trials, and contrasted between *in vitro* and *in vivo*. They referred to (and listed) USPHS (Ryge) criteria and the use of replica models and laser techniques for measuring marginal integrity and surface wear. They touched on the issue of examiner calibration and considered issues which resulted in only short-term evaluation of commercial products. They concluded that the future for dental restoratives clinical research should involve more statistically powerful trials.

In a study by Mair (1998), thirty restorations of each of five materials were placed in 1985, assigning cavities randomly. The research was carried out in a dental school environment. Clinical measurements of wear and colour-match were carried out at base (within 2 weeks of placement) and at 6 months, 1,2,3,4,5 and 10 years. Wear was measured using an impression technique, involving filling the gap between the baseline impression and the ten-year cast of the same tooth with a yellow light-bodied material, and then examining 300μm sections using incident light microscopy.

2.5 Data Collection Methodology

2.5.1 Hierarchy of Evidence

The methodologies used for the assembly of evidence in the dental literature are many and varied. Several authors subscribed to the view that there was a hierarchy of evidence, and that certain types of research were intrinsically better than others. Downer et al (1999) conducted a ‘systematic review’ of 124 research reports. Of these, 58 were considered relevant, and eight of these were categorised as being of satisfactory validity and quality, against a list of criteria. A lot of the criteria cited begged or prejudged questions about what ‘good’ research involves. The paper contained a useful discussion of methodology and measures for survival analysis. It also referred to the arguments put forward by Mjör (1997) and others concerning the merits of unstandardised 'real practice' cases.

In forming their list of criteria, Downer et al (1999) were influenced by the Cochrane Collaboration and the NHS Centre for Reviews and Dissemination, several of whose reviews have already been cited (eg Dummer et al (2000), Jones et al (2000)).

The paper by Treasure et al (2000) considered the information which, in best practice, would be included in a research report:

1. **Description of recruitment and randomisation**
2. **Description of population characteristics**
3. **Details of subjects/restorations lost to follow-up**
4. **Description of outcome measures used**
5. **Number of subjects and restorations:**

placed at baseline
placed at each review for the whole study
placed for all subgroups.

Dunstan et al (2000) considered the question of how to create a meta-analysis of studies with different methodologies. They reported that, for example, paired studies showed less difference in longevity between amalgam and composite than other studies. Weighting by methodology was problematic. Using study design as a factor in Cox's proportional hazard model suggested a significant systematic difference between the results from different methodologies. Possible explanations included systematic bias in reporting, recruitment, or early termination. They recommended that the following should be reported for all studies:

1. **Frequencies, not percentages of failures**
2. **Full information on drop-outs**
3. **Complete information on failures, including time of failure or last intact assessment**
4. **Full details on selection and randomisation of patients and information on effect modifiers.**

Nishimura et al (2002) described a statistical analysis of a body of literature on a particular subject, in this case dental prosthetics. Using MEDLINE, a total of 10,258 articles, over a ten-year period, were retrieved using a range of more or less relevant dental terminology for text searches. These were spread across more than sixty different journals. However, a more specific search retrieved less than one tenth of this number. The authors concluded that the increasing volume of possibly relevant articles being published is such that there may be a need for computer based knowledge systems to provide real-time clinical decision support.

Sheldon and Treasure (1999) restricted the papers they included to Randomised Controlled Trials (RCTs) and similar studies, mostly in a dental school setting. They recognised the gap between ideal conditions and what happened in practice. They also criticised many studies for not providing enough detail about numbers of subjects, teeth, the tooth types, the materials and the types of cavities. No studies extending more than five years were cited. Their paper contains a useful checklist of objective (patient, tooth and operator or restoration) and subjective (incentives, patient preferences, treatment philosophy) modifying factors.

2.5.2 Randomised Controlled Clinical Trials

The randomised controlled clinical trial has been regarded as the ‘gold standard’ for medical, and hence for dental, research. This can be seen for example in the hierarchical classification in Downer et al (1999). A history of the development of this method of research can be found in Randall and Wilson (1999b). This paper contrasted the history of medical research with that in dentistry. It covered methodological development from Hippocrates through to Bradford Hill. Most clinical trials were epidemiological (eg fluoride in drinking water). The paper contrasted therapeutic and observational, prospective and retrospective studies, and the benefits of randomisation. The authors also considered ethics and the need for informed patient consent. They concluded by referring to the Oral Health Group of the Cochrane Collaboration and discussing the relative merits of randomised controlled trials (RCTs) and involvement of GDPs in practice-based research.

Davies (1987) discussed some of the problems, mostly associated with censoring, which distinguished dental restoration survival data from its medical equivalent:

1. **Size of study**
2. **Length of study compared with median life**
3. **Proportion of the data censored**
4. **Quality of information on the censored data.**

She demonstrated the effects of different lengths of run of data series, and different assumptions about censoring when applied to the Scottish GDS follow-up survey (Elderton, 1983b). In dental studies it was difficult to determine when, in a long open gap following the last recorded attendance by the patient, censoring should be considered to have happened.

The elements of a randomised controlled clinical trial can be broken down as follows:

‘Controlled’ means that in addition to analysis of the treatment under investigation, a parallel analysis is carried out of the standard existing treatment (or a placebo), under the same controlled experimental conditions

‘Randomised’ means that the experimental subjects (eg tooth, restoration, patient) are allocated to the treatment or the control by a random method, to avoid systematic differences between the two groups of subjects.

‘Clinical’ means that the research deals with treatments conducted on live patients, as opposed to *in vitro* experiments.

A randomised controlled clinical trial is therefore necessarily prospective, and to the extent that successive measurements or other records are captured over time for the same experimental subject, it is necessarily longitudinal. There are also examples of longitudinal studies which are not randomised, or not controlled, or not clinical.

Jokstad et al (2002) described an analysis of the quality of research papers reporting on RCTs in prosthodontics. A total of ninety papers were each evaluated by at least two assessors, drawn from three clinical assessors and a dental statistician. The statistician reviewed all the papers. Overall the quality of reporting was poor, particularly with respect to the methods used to secure randomisation. It was noted that those papers reported in medical journals were of generally better quality, and the authors suggested that the editorial and review process could do much to improve the quality of reporting of research. In particular, they commended the adoption of the CONSORT recommendations in publishing RCTs.

An example of a longitudinal study where randomisation was not considered appropriate may be found in Jokstad and Mjör (1991a and 1991b). This study covered 210 Scandinavian patients in general practice. Of the seven dentists, three were in private practice, two in public health service, and two in school dental service. Data were gathered on 468 class II (interproximal) molar or premolar restorations placed between December 1979 and January 1983. Several different amalgam alloys were used, and the teeth were re-examined every year using USPHS criteria. Patients were classified in levels of caries activity according to the number of new restorations provided per annum. MCA - multiple classification analysis (regression on categorical variables) was used to regress on eight significant factors: operator, patient caries, patient age, alloy, tooth position, type of filling, patient gender. Alloy and gender were least important. Life table analysis was carried out using 6 month periods, from which survival was estimated at 90% to 48 months, and 81 % to 114 months.

Until recently there have been relatively few examples of randomised controlled clinical trials in research into the survival of dental restorations. Those that do exist tend to be small scale and of short duration. The methodological requirement for controls and randomisation is difficult to combine with the ethical requirement for informed patient consent in a general practice environment.

One example where such a trial has been completed was given by Wilson et al (2002). In many ways, this was a model example of a randomised controlled clinical trial. Its purpose was to compare two restoration materials. Patients were chosen from regularly attending consenting GDS patients who had pairs of similar lesions or failed restorations. Careful exclusion criteria were employed, the two materials were randomly distributed between the pairs, and the teeth were inspected within one month of restoration placement, and again at six months and at one year. Criteria for assessment were set out, similar to USPHS, and the examinations were carried out by two calibrated investigators. Diestone replica models were created from impressions, and assessed blind by one investigator.

Unfortunately, the number of participants - 50 patients - was too small, and the follow-up period - one year - was too short, to have sufficient power to detect anything other than gross differences between the materials. Furthermore, the absolute values achieved, because of all the controls, are far removed from the typical performance of restorations in general practice.

Another example of good randomised controlled clinical trial experimental design can be found in van Dijken (1996). This involved the comparison of three materials over a 3 year period. Data from fifty patients, with 154 class III restorations evaluated by USPHS at six months, and at one, two and three years. All bar two lasted the three years. The author did not state the environment, but it appears that this work was conducted in a dental school setting rather than in general practice. As with the previous study, the number of participating patients was small.

Plasmans and van't Hof (1993) described a randomised controlled clinical trial on extensive amalgam restorations (EAR). Three operators placed 300 EAR on molar teeth, using five different auxiliary retention methods. After four years, the total number of 'failures' was only 31, so it was too early to draw any conclusions about the relative merits of the different methods. A distinction was drawn between 'relative-restoration', 'relative-endodontic' and 'absolute' failure. There were seven absolute failures, five of which were placed by the operator with hardly any experience of EAR.

Plasmans et al (1998) reported the longer term results of the same study. Only 3% of the patients dropped out of the study. The analysis distinguished three different types of survival : a) still functioning, and no maintenance treatments, b) still functioning, but eventually treated with one or more maintenance treatments and c) as a) or b) or covered by a crown, and therefore functioning as a substructure.

Di Lenarda et al (2000) described a prospective randomised clinical trial designed to determine whether acid etching of cavities improved the performance of cervical compomer (polyacid-modified resin composite) restorations. Sixty restorations, randomly allocated between those with acid etching and those without, were evaluated every six months, up to 48 months, using modified USPHS criteria (as described in section 2.4.2). Kaplan-Meier analyses were used to determine survival of alpha ratings. For most of the USPHS criteria, including restoration failure, there was no significant difference between the two groups. The exceptions were marginal discoloration and marginal adaptation, which were significantly worse for the restorations which had not received cavity etching.

Mair (1998) described a study in which thirty restorations of each of five materials were placed in 1985, assigning cavities randomly. The study was carried out in a dental school environment. Clinical measurements of wear and colour-match were carried out at base (within two weeks of placement) and at six months, one, two, three, four, five and ten years. Only 61% of the patients were traceable after ten years.

Einwag and Dunninger (1996) described a paired comparison study on 106 primary dentition patients. Each patient received one multi-surface amalgam and one stainless steel crown, and subsequent survival was measured using the Kaplan-Meier method. The results showed clear superiority of the stainless steel crown, which achieved over 90% survival after 4.5 years, when the amalgam survival had dropped below 40%.

Van Dijken (2003) carried out a smaller study of two alternative composite resin techniques. It was too small to detect differences between the two techniques, though the study design was good. After some dropout of patients, 41 pairs of restorations (each pair in the same mouth) were evaluated after 6 years using modified USPHS criteria. Only one restoration of each type was considered to have failed, so clearly no difference was detected.

Raskin et al (2000) described a prospective randomised clinical trial to compare two isolation methods for posterior resin composite restorations. A single operator placed 100 restorations, with 52 randomly assigned to cotton roll isolation and 48 to rubber dam. The restorations were assessed at baseline and at six months, annually to six years, and finally at ten years, using a modified USPHS rating system. Survival was measured using life-table analysis. No significant difference was found between the two groups.

Mandari et al (2001) described a comparison of ART (Atraumatic Restorative Treatment) against conventional and modified conventional restorations using amalgam and glass ionomer in occlusal surfaces. A sample of 152 school children, each of whom needed at least two restorations, were allocated randomly to three groups. Each group received one of the three treatment regimes. Within each child's mouth, at least one amalgam and one glass ionomer restoration were placed. All restorations were placed by the same operator.

Restorations were assessed at baseline and two years later, using modified Ryge-USPHS criteria. The same two dentists who carried out the baseline examination also carried out the two year review, and they were checked for inter-evaluator consistency.

There are more examples of randomised controlled clinical trials to be found in the dental school environment. Letzel et al (1997) described a secondary analysis of fourteen such trials at the University of Nijmegen Dental School. As Letzel et al (1998) acknowledged, the patients for all these studies (mainly selected from university students, staff, and their relatives) were selected because of their interest in dentistry, their high level of oral hygiene, and their need for at least six restorations. Their validity as a basis for inference in other environments depends on assumptions about whether, in respect of the topic being researched (in this case alloy influences on the survival of amalgam restorations), the systematic differences between the patient populations can be neglected.

2.5.3 Retrospective Cross-sectional Studies

A commonly reported research design, particularly in general dental practice, is the retrospective cross-sectional study, usually looking at restorations which have been replaced, or have failed in some other way, over a short observational period. Examples include Mjör (1997), Mjör and Medina (1993), York and Arthur (1993), Lavelle (1976), and Friedl et al (1994). Jokstad et al (1994) reported on a cross-sectional analysis of restorations *in situ*.

Manhart and Hickel (2001) discussed the differences between longitudinal and cross-sectional studies, and the limitations of each.

Many cross-sectional studies are primarily concerned with the reasons for replacement of restorations, and the distribution of ages of the restorations replaced is quoted as an easily calculated bonus. However, Letzel et al (1997) observed that, although such studies were quick to perform, the results may not be compared with those of survival studies, because replacement studies do not give information about survival.

2.5.4 Longitudinal Clinical studies

Mjör (1989) considered the desirability, but dearth of, longitudinal studies of longevity. He referred to the acceptance program of the American Dental Association (ADA) for composite resin materials, which required a five-year longitudinal study, in which a failure rate of up to 10% in five years was considered acceptable, using the Ryge system of evaluation.

Most of the longitudinal studies in the literature lack either the randomisation or the control element which would qualify them for inclusion as randomised controlled clinical trials. They therefore need to be interpreted with caution. Some of the examples given relate to indirect restorations or bridges.

One example is the paper by Hujoel et al (1998). This described a longitudinal study of 565 Norwegian males first recruited as young adults in 1969. All attended their dentist regularly. This is a study of tooth mortality (which approximates to cumulative restoration mortality). The data are affected by interval, left, and right censoring. Survival analysis was carried out on data grouped by decade. The analysis techniques used were Kaplan-Meier to describe the data, and Cox Regression with number of teeth present as covariate for modelling.

The observed results were as follows:

Very few teeth were lost during the 26 year observation period. Tooth mortality was greater for posterior than for anterior teeth. Drop-out was informative (t-test). The hazard function appeared bathtub-shaped, so Weibull modelling was inappropriate.

This paper is a useful source for the application of the statistical package SAS to dental data, but the findings are neither conclusive nor particularly surprising or interesting, in view of the self-selected nature of the patients, the informative censoring, and the uncertainty over the reasons for the high apparent tooth loss in the years prior to 1969. The discussion does not mention changes in intervention philosophy over time - this would be a major consideration if the data had related to events in England.

Mjör et al (1990), in a review paper, considered it unrealistic to expect controlled longitudinal prospective studies to last more than 10 years. These workers recommended taking account of restorations which have not failed, and concluded that 'a wealth of data are present in dental offices around the world, but their collection and especially the statistical analyses of the data is difficult'.

Qvist et al (1997) reported on a study over three years of longevity of restorations in primary teeth. The subjects were 666 children, with 515 glass ionomer fillings and 543 amalgams. Overall, glass ionomer median survival time was 34.5 months, and the upper quartile for amalgam (on class II cavities) was more than 36 months.

The study by Robinson (1971) covered a 21 year period. However, the sample was highly selective - patients who left or had gaps in attendance were excluded. The median failure time was about ten years.

Crabb (1981) carried out a study of long-term patients attending Leeds Dental Hospital. Restorations were restricted to those which had either failed within 10 years or were known to have survived more than 10 years. Crabb noted the systematic difference between hospital and general practice - satisfied patients may not return to hospital.

Drake (1988) produced a longitudinal study of 71 patients over 29 years, all treated in a school of dentistry. There were 1,232 restorations in all. He used Robinson's criteria (section 2.4.1) for failure, and Kaplan-Meier plots for comparing maxillary and mandibular survival for restorations in each of four categories: molars, pre-molars, canines and incisors. No significant difference was found except for incisors, where maxillary incisor restorations failed earlier. His estimates of ten-year survival rates ranged from 57% for maxillary incisors to 82% for molar teeth.

Smales and Hawthorne (1997) conducted a retrospective study of 100 patients at three surgeries in Adelaide, drawn randomly from regular attendees. There were 430 crown or extensive amalgam restorations. Mean follow-up time was about 25 years. They used life table analysis and found that longevity of crowns was greater, although that of amalgam was still impressive.

In a related paper, Hawthorne and Smales (1997) described a long-term retrospective study of restorations placed in another 100 patients randomly selected from patients who had attended one of three Adelaide private dental practices since before 1980. A total of 2,931 dental restorations including 1728 amalgams, 458 composite resin and 275 glass ionomers, by a total of 20 different dentists, were included in the study. Attendance periods ranged from 10 to 46 years. The median survival times were calculated as 23 years for amalgams, 17 years for resin composite, and in excess of 11 years for glass ionomer.

Strand et al (2000) described a study of 252 patients of mean age 16 in two public dental districts in Norway. All these patients were offered a tunnel restoration as an alternative to amalgam. Twelve dentists were involved, all initially inexperienced in the technique. A total of 420 restorations were placed, using Ketac-Silver (a cermet material). There were subsequent annual examinations, using modified USPHS criteria. Analysis was by Kaplan-Meier, using log-rank to compare groups, with no adjustment for frailty. The maximum observation period was 54 months, and 43% of the restorations were classified as having failed within this time.

Geurtsen and Schoeler (1997) made a study of 1,209 posterior restorations on 412 patients placed by one dentist working in private practice in Norway. Restorations were graded according to criteria described by Ryge and Snyder, using two observers. Follow-up ranged from 12 months to 4.5 years. The estimated survival rate at 4 years was 87%.

Clarkson et al (2000) conducted a longitudinal study over five years of patients regularly attending 24 general dental practitioners in the North West of England. The number of patients at baseline was 3,920, and 2,799 of these were seen in the final year. This study charted the subsequent restoration experience of 55,437 teeth, by tooth position, type of restoration, and reason for restoration, for the 2,293 patients who were examined every year. It also recorded the retreatment rates for the restorations placed in the first year.

Odén et al (1998) described a five-year prospective study of 100 Procera AllCeram crowns. The 58 patients were chosen as consecutive crown patients of four Swedish general dental practitioners. Three cases were lost to follow-up. By the end of five years 65 were still classified 'excellent', 26 'acceptable', and 6 had been replaced.

Berg and Dérand (1997) conducted a similar evaluation of Cerec porcelain inlays over a five year period. Initially 46 patients with 115 inlays were chosen from one private dental practice in Sweden, but 14 dropped out within five years. The inlays were evaluated by using a scanning electron microscope to measure the width and depth of marginal ditches on an epoxy resin model of the tooth. In all 51 inlays were evaluated.

Burke and Qualtrough (2000) described a two-year follow-up study on surviving dentine-bonded crowns which had previously survived 2.4 years (on average). Of 23 patients whose restorations were intact in 1996, 20 were successfully re-examined in 1998. They had 53 intact restorations in 1996, of which 48 were still intact in 1998. These restorations were examined using modified USPHS criteria.

Another small study on crowns was conducted by Bindl and Mörmann (2002). They analysed the records of 21 patients who each had one or other, or both, of two different CAD/CAM all-ceramic crowns placed in 1995. In 2000 the patients were recalled and examined using USPHS criteria. Kaplan-Meier charts were drawn, but with so few patients and such short follow-up time, they did no more than confirm that most of the crowns survived the first five years.

Fradeani and Redemagni (2002) did a retrospective analysis of 125 all-ceramic crowns, out of an original 170 placed on patients consecutively attending two private clinics in Italy. Five patients were lost to follow-up and removed from the study (not included in Kaplan-Meier analysis). The crowns were re-examined after an initial six months, and annually thereafter. Follow-up ranged from four to eleven years. The examination used modified CDA and Ryge criteria, and any cases coded Charlie or Delta were replaced.

Walton (2002) conducted a study of the longevity of bridges placed by one dentist in Australia. The data consist of records for 515 metal-ceramic fixed partial dentures comprising 1,209 abutments and 885 pontics provided for 357 patients between 1984 and 1997. Kaplan-Meier analysis was used for both pontics and abutments. Ten year survival rates were over 75% for both. Non-vital abutments had much worse survival than those on vital teeth. The survival curves showed a considerable increase in failure rate over time.

Djemal et al (1999) gathered together all the historical data for resin-retained bridges and splints placed by the Eastman Dental Hospital. Their paper is useful from a methodological point of view, discussing such issues as the criteria for failure, including feedback from patients on whether they had noticed symptoms of failure. Both life-table and Kaplan-Meier analyses were used to describe the survival behaviour, and the authors discussed the extent to which the survival curve could be dominated by the small number of cases which had survived for a very long time.

2.5.5 Large-scale Administrative Databases

Until recently, the largest study using an administrative database as a foundation was that by Elderton (1983b). This involved the linking of 720 dentate adult records from the Adult Dental Health Survey to subsequent Scottish Dental Division (SDD) administrative records. The SDD is the Scottish equivalent to the DPB. It is interesting to note that Elderton confined his work to such a sample survey in the light of the Dental Strategy Review Group view that 'the establishment of any national centre with provision for such linkage of records over an extended period, however desirable, would be a massive and expensive undertaking'. Elderton used life table analysis on five years' data to estimate median survival time for directly placed restorations (amalgam and synthetic) at less than five years.

Patterson (1984) conducted a retrospective study of 3,299 restorations on 200 regular patients attending a large NHS practice in NE England. Life tables were used to estimate survival. Over the study period 1967-1983 one principal and sixteen full- and part-time assistants worked in the practice. Patterson found that the median survival times were 7.5 years for amalgam, 5.5 for silicate, and 4.25 for composites. This study suggested that restorations placed in a regular attendee at a dental practice were likely to last longer than was suggested for the general population by Elderton.

Robbins and Summit (1988) reviewed some 10,000 dental records for staff and family of the United States Air Force (USAF), from which 209 patients with one or more complex amalgam fillings were identified. Patients with certain medical histories were excluded. Complex was defined as involving the replacement of one or more cusps. There were 43 failures identified in 35 patients. No cause of failure could be inferred from the records.

The administrative analysis was then followed up by clinical examination of 86 patients with 128 complex fillings placed at least five years earlier. The examination involved the use of four current bitewing radiographs and a sharp #23 explorer.

The following criteria for failure were used:

1. **Marginal - acceptable or unacceptable**
2. **Fractured tooth adjacent to restoration**
3. **Fractured restoration**
4. **Caries associated with restoration**
5. **'Occlusal morphology inadequate for masticatory function'**

There were two examiners, calibrated on twelve patients. Restorations were further classified according to surface coverage and molar vs premolar. Statistical techniques used included life table analysis and Duncan's multiple range test. A summary of the results on longevity is presented in the next section of this chapter.

Smales et al (1991a) carried out an assessment of long term predictions of longevity (up to 17 years). The analysis involves fitting a Weibull model to progressively shorter sets of life-table data. The data covered 1,345 restorations on 100 members of the Royal Australian Air Force (RAAF).

Gilthorpe et al (2002) produced a paper which is important from both a statistical methodology and risk factor point of view. It describes analysis of the posterior amalgam records of 200 RAF (Royal Air Force) personnel over a period of at least sixteen years in each case. Single and multi-level Cox regression models were fitted, and the following factors were found to be associated with a higher risk of failure: molars compared with pre-molars, large restorations compared with small, and the presence of root treatment or pins. Those patients who had seen more different dentists had more restoration failures, as did those with a higher number of decayed and filled teeth on entry into the RAF.

The paper by Bogacki et al (2002) is described in detail earlier in this chapter. With the advent of more powerful computers the mining of administrative databases is, at last, becoming possible. This is the closest study in terms of content to the area covered by the present work. Bogacki et al (2002) used their data warehouse as a source for selecting patients with particular characteristics, then followed their life histories, as recorded on the database.

An alternative, aggregate, analysis of the same (Washington Dental Service) database can be found in the paper by del Aguila et al (2002). This paper consists of a descriptive statistical comparison of dental treatment activity between the years 1993 and 1999, within the Washington Dental Service (WDS). The study noted that, despite the projections based on oral health trends, the patterns in the two years were very similar. The WDS had records of over 1.25 million people, with their dentists representing over 80 percent of practising dentists in Washington State.

The patterns in the WDS have many parallels with those of the GDS in England and Wales. There had been growth in Specialty Practices - endodontics, surgical, orthodontics, pediatrics, periodontal, and even in prosthodontics. This latter change was probably attributable to implants (permitted since 1998). From a low base there had been a dramatic increase in the provision of implants. Of greater relevance to the GDS was a 40% reduction in amalgams, and a 30% increase in composite resin - across all age groups. One major possible difference was the apparent volatility of the patient base - only one third of the patients treated in 1999 were also treated in 1993. There were also intermediate changes in policy, such as the change in implant re-imbursement. The paper also contains details of a sample validation check on the quality of the central records, compared with records held within the dental surgeries.

2.6 Main Empirical Findings on Longevity

Apart from the differences in definition of the events which mark the start and end of the ‘life’ of a restoration (as described in section 2.4), the distribution of that life across a population may be described by a variety of statistical measures. In most published papers either the average life-span (measured by mean or median), or the expected proportion surviving at the end of a specified interval, such as five or ten years, has been quoted, generally surrounded by a confidence interval. Where the time-span of the research was limited, the latter type of measure has been favoured, since in such circumstances there may be insufficient data to estimate the mean or median directly. Ideally, a complete characterisation of the survival curve would be desirable, from which any necessary statistic could be derived. The limitations of available data generally preclude such a presentation of findings, though some authors, such as Smales et al (1991a), explored the extent to which the observed survival curve could be modelled by a specific mathematical function such as a Weibull distribution.

2.6.1 Long Term Studies

Studies where the oldest restoration recorded was more than five years old provide the most complete picture of the life of restorations, but they tend to be restricted to a small sample of relatively unusual patients. Smales et al (1991a) used data for 100 members of the Royal Australian Air Force. Using life-table methods, they estimated median survival at around 14 years, and ten-year survival at around 60%. Their study was restricted to amalgam restorations, and ignored what were described as ‘apparent’ failures, where apparent failures were described as those caused by unrelated tooth extractions, endodontic treatments, incorporation into other restorations or damage from trauma. In that study, apparent failures accounted for only 10.6% of the total replacements. Gilthorpe et al (2002), also dealing with amalgam restorations, estimated crude median survival time at 10.9 years at subject level and 8.4 years at restoration level.

The study by Elderton (1983b) covered only five and a half years, but a re-interpretation of his data could suggest that he has in effect covered nearly twice that period, since he started with restorations *in situ*. His work involved the linking of 720 dentate adult records from the Adult Dental Health Survey (ADHS) to subsequent treatment records created by the Scottish Dental Division. He used a life table analysis, but his analysis used the data from the ADHS only as background data about the patients and their state of oral health. He concluded that the median survival time for amalgam restorations was 56 months and that for synthetic restorations was 55 months.

Davies (1987) revisited Elderton's study, and commented on the dangers inherent in assuming that a patient's record should be censored on 'date-last-seen'. She noted that in dental studies it was difficult to determine when, in a long open gap, censoring should be considered to have happened. She showed how the estimate of median survival time was sensitive to variations on Elderton's assumption. Assuming a 75% return rate on some date subsequent to the end of the follow-up period for restorations *in situ* at the last visit led to an increase in the estimate for amalgam restorations from the original 55 months to 94 months, much closer to the range of estimates produced in other studies.

Jokstad et al (1994) considered the age of restorations *in situ*, using records from a single practice in southern Norway. Median ages of 12-14 years were found for amalgam restorations and 7-8 years for composite resin. There was some variation with the length of the available treatment record, with the median age stabilising after sixteen years of records were available for amalgam restorations, and after 7-8 years for composite resin.

Lavelle (1976) combined a cross-sectional survey of 3,000 defective amalgam restorations on new patients with a longitudinal analysis of the 20-year records of 200 regularly attending adult patients. For both exercises the patients were drawn from those attending three similar general dental practitioners. From the longitudinal analysis he concluded that the median survival was around ten years, and that less than ten per cent lasted for 20 years or more.

In another small practice-based study which has been described earlier, Robinson (1971) estimated around ten years for median amalgam survival and almost a quarter lasting more than twenty years. A similar study by Patterson (1984) found that the median survival time for amalgam was 7.5 years, with corresponding figures of 5.5 for silicate and 4.25 for composites.

Crabb (1981) described a study based on the records of dental school patients. He quoted ten year survival rates of 40-60% for amalgam, depending on type, and 11-21% for silicates, and five year survival of 54-78% for composite resin, again depending on type.

Drake (1988) studied 71 patients over 29 years, all treated in a school of dentistry. There were 1,232 restorations in all. He used Robinson's criteria for failure, and Kaplan-Meier plots to estimate empirical survival statistics. He compared different tooth positions, with the following results:

Tooth Position	**Ten-year Survival**	**Median Survival**
Molars	82%	21 years
Premolars	80%	23 years
Canines	75%	16 years

Maxillary incisors	56.9%	11.4 years
Mandibular incisors	74.9%	26 years

Jokstad and Mjör (1991a) considered several different factors affecting longevity of class II amalgam restorations in a longitudinal study of 210 Scandinavian general dental patients. Life-table analyses were used to estimate underlying survival rates of 90% survival to 48 months, and 81% to 114 months.

Smales (1991) described a study in which a total of 768 amalgam restorations were placed in Class II cavities on 332 premolar and 436 molar teeth in a dental hospital. Of these, 124 involved cusp coverage. Life table analysis was used to estimate survival over 15 years. For both cusp-covered and those without cusp coverage overall cumulative survival was 73% after 15 years. Survival was poorer when pins were used, and for older patients, but the sample was not large enough for these clinically important differences to achieve statistical significance.

Smales and Hawthorne (1997) conducted a retrospective study of 100 patients at three surgeries in Adelaide, drawn randomly from regular attendees. They found the following survival percentages for amalgam restorations at five, ten and fifteen years respectively: 77.6%, 66.7% and 47.8%. Median survival time was estimated at 14.6 ± 1.2 years.

Hawthorne and Smales (1997) conducted a more extensive study on a further 100 patients attending the same surgeries. A total of 2,931 dental restorations including 1,728 amalgams, 458 composite resin and 275 glass ionomers, by a total of 20 different dentists, were included in the study. Attendance periods ranged from 10 to 46 years. A combination of Elderton's and Robinson's criteria for restoration failure was used, and the median survival times were calculated as 22.5 years for amalgams, 16.7 for resin composite, and in excess of 11.2 years for glass ionomer.

Robbins and Summit (1988) studied the records of 209 members of the United States Air Force, chosen because they had complex amalgam restorations. They found that 75% of the restorations survived 5.7 years, 50% (median) survived 11.5 years, and 25% survived 16 years, with survival rates of 54% at 10 years, 36% at 15 years and 19% at 20 years.

Aalen et al (1995) looked at the survival behaviour of amalgam fillings in a sample of 32 patients from seven dentists in Oslo. Although the main theme of the paper was statistical, the observed ten-year survival rate was about 70%, with a near linear cumulative survival curve over a thirteen year observation period, suggesting an increasing hazard function.

Clarkson et al (2000) described a longitudinal study over five years of patients regularly attending 24 general dental practitioners in the North West of England. There were 3,920 patients at baseline, and 2,799 of these were seen in the final year. The authors charted the subsequent restoration experience of 55,437 teeth, by tooth position, type of restoration, and reason for restoration, for the 2,293 patients who were examined every year. In particular they recorded the retreatment rates for the restorations placed in the first year. One year retreatment rates were 12% for amalgam and 11% for tooth coloured restorations.

Roulet (1997) conducted a comparison between glass ceramic inlays and amalgam restorations placed by one dentist, evaluated using modified USPHS criteria, over up to 82 months. The data comprised 123 Dicor inlays on 29 patients and 163 amalgam restorations on 43 patients. The amalgam restorations were chosen as a matched comparison set, with similar distribution between class I and class II and between molar and premolar teeth. Kaplan-Meier analysis was used to plot empirical survival curves with 95% confidence intervals. The study found no significant difference between the two types of restoration, with an estimated survival rate of 87% after six years for amalgam restorations, so the inlay was considered a clinically acceptable alternative to amalgam. All inlay failures were attributed to poor case selection. Since inlays cost about eight times as much as amalgams, Roulet concluded that amalgam could be more cost-effective.

Bogacki et al (2002) measured five-year and seven-year survival rates for particular subgroups of a dental insurance population. For patients who stayed with the same dentist, they estimated five-year survival at around 94% and seven-year at about 92%. For patients who saw a different dentist, the seven-year estimated survival rate dropped to 60%.

Van Dijken (2003) provides a useful summary of recent studies of longevity of posterior composite resin restorations, with five year failure rates ranging from 2% to 28%, and ten year rates from 10% to 64%.

2.6.2 Short Term Studies

Although short term studies (under about five years follow-up) give no information about long-term behaviour, they are particularly useful for recently introduced materials and techniques, and form a safety-net against premature failure. The short follow-up period lessens the distortion associated with censoring assumptions, and the proportion of cases censored for reasons other than the end of the overall follow-up period is typically small.

Jones et al (2000) summarised the findings from 32 studies of composite restorations and 14 glass ionomer. In total there were 3,419 composite and 1,078 glass ionomer restorations. Most of the studies (55%) were randomised controlled trials, 33% were prospective case studies, and 12% other clinical trials. The trials lasted up to 48 months. Overall, glass ionomer was better than composite, but the best composite was better than glass ionomer. Etching improved survival. One-year survival ranged from about 60% to over 95%.

Cunningham et al (1990), in research related to that by Mair (1998), reported on a study in which a total of 605 restorations were placed - by one hospital dentist and two GDPs. After three years 309 composites and 200 amalgams were evaluated. There was no significant overall difference in survival proportions, but amalgams had more mechanical marginal deterioration, while composites had more caries. One of the composites (Clearfil Posterior) was considered unacceptable for colour match. At three years 6% of composites had failed, and 5.8% of amalgams.

Geurtsen and Schoeler (1997), in their single private dentist Norwegian study, estimated the survival rate for posterior composite restorations after 4 years at 87%. With extrapolation using a fitted Weibull model, the median survival time was estimated at 9 years. Survival of premolar restorations was significantly better than that of molars.

Crisp and Burke (2000) described a follow-up study of 100 restorations involving the use of F2000 (3M, St Paul, MN, USA) compomer. Compomers were first introduced into Europe in 1993, and the manufacturers originally expected the material to be used for non load-bearing restorations - classes III and V. Six private general practitioners participated in the study, and their work was examined after an average of 14 months by one examiner from the Unit of Dental Practice at the University of Glasgow Dental School. The evaluation followed modified Ryge criteria. In the event, only 84 of the restorations were available for examination. It is not clear what happened to the other 16. Of the 84, there were 61 in Class III or Class V cavities, and three of these had been lost - two had fallen out and one had been replaced by a crown. Contrary to instructions, the dentists had placed the other 23 restorations in load-bearing situations - classes I, II and IV. Performance was acceptable in all respects, except for about 3%, where colour match was rated unacceptable by the evaluator. Even here, as in all other respects, all the patients were satisfied with the material.

Smales and Yip (2002) produced a review of longevity studies of ART glass-ionomer restorations. ART involves use of hand instruments only and minimal removal of tooth substance, generally without local anaesthetic. The material used is generally conventional or reinforced glass ionomer cement. Simple survival rates over one, two and three years are quoted, generally without sample sizes. For single surface (class I and V) restorations of permanent teeth the reported success rate is around 90% after two or three years, and significant differences have been reported for different operators. The conclusions were equivocal - further improvements to glass ionomer cements were needed and, in the absence of long term studies, the recommendation was that the ART approach be restricted to single-surface carious lesions in permanent teeth, and to fissure sealants.

Mandari et al (2001), in the study comparing ART and conventional techniques described earlier, found that none of the differences between the survival rates at two years, which ranged from 89% to 99%, was significant, though the ART survival was lower, for both materials, and the authors suggested that differences might become more apparent over a longer time period than two years. Other factors, such as diet and health care, would however become more important over a longer period. Nevertheless, the overall conclusion was that, for countries facing scarcity in resources for dental care, ART seemed a promising restorative approach for the treatment of occlusal caries in posterior teeth.

2.6.3 Opinion Surveys

An alternative, indirect, way of measuring the life of restorations is to ask clinicians for their professional opinions, based on years of clinical experience. Such an approach can provide an insight and an overview which other methods, involving examining patients or their clinical records, may not reveal.

Burke et al (1999) conducted a study of work of 56 Vocational Dental Practitioners (VDPs) and 17 trainers. This involved 9,031 restorations. Participants were asked to give reasons for placement/replacement, plus type and age of filling material. The proportion of replacement was 51% overall. Primary caries (41.3%) and secondary caries (21.9%) were the two main reasons for placement/replacement. Amalgam restorations appeared to have significantly greater longevity than composite or glass ionomer.

Maryniuk and Kaplan (1986) sought the views of 571 interested dentists, recruited from professional meetings and courses. The response rate was 46%. The questionnaire asked about how each dentist would treat a hypothetical 35 year old regular attendee with minimal or no periodontal disease and with acceptable oral hygiene. Respondents were asked to give expected and observed longevity of small (1-3 surfaces) and large (4+ surfaces) amalgams and cast restorations. They estimated that 71% of restorations were on previously restored teeth, and 84% had been done by a previous dentist. The key findings were as follows:

Type of restoration	Ideal life	‘Average’ Life	Minimum Acceptable Life	Full fee replacement time
Small Amalgam (1-3 surfaces)	16.7 years	11.2 years	6.5 years	3.0 years
Large Amalgam (4-5 surfaces)	9.3 years	6.1 years	4.0 years	2.2 years

Dentists considered that their own restorations lasted longer than those of other dentists. They considered responsibility for failures to be distributed as follows: 47% patients, 30% dentists, and 23% materials.

Mjör and Moorhead (1998) considered reports from 27 clinicians in Florida on restorative materials, reasons for replacement, and age of restorations replaced. Longevity, based on records held by clinicians, was 15 years, median and mean, for amalgam, and 8 years for composite.

Clarkson et al (1995) considered four different methods of assessing the national state of dental health:

1. **Trained and calibrated examiners collecting detailed clinical data - as used in national surveys, but very expensive**
2. **Direct questionnaire to public - accurate for the more simple measures, and has been used in the General Household survey**
3. **DPB - limited to GDS, and doesn't supply reasons for treatment, and,**
4. **Direct approach to GDPs.**

This report considered the feasibility of collecting, and comparability, of data reported by a set of 24 volunteer dentists from the Greater Manchester area. These dentists charted the state of mouths of their regular patients. The results were found generally to be similar to those for regular patients in the national survey of adult dental health.

2.7 Risk Factors

2.7.1 Materials

The performance of different restoration materials, both relatively and in absolute terms, is of great practical interest both to the clinician and to the patient. The properties of the three main types of material used for dental restoration - dental amalgam, composite resin, and glass ionomer - were discussed by Going and Jendresen (1972). Mjör and Qvist (1997) considered the failure modes of different materials.

Phillips et al (2000) considered the costs of different materials, both on a single filling basis and over the lifetime of a tooth. Sheldon and Treasure (1999) also carried out an economic evaluation of different materials, and concluded that amalgam was the most cost-effective. Jedynakiewicz and Martin (2001) also stressed the need to consider the whole life expectancy of the tooth, not just the immediate cost of restoration.

The economics of restoration replacement was also considered by Sjögren and Halling (2002). Their paper combined existing longevity data with social insurance fees and patient charges in Sweden to compare the long-term (over ten years) costs of amalgam, composite resin and glass ionomer restorations of class II cavities in molar teeth. Despite the current zero social insurance fee for amalgam (for environmental reasons), composite resin was consistently more expensive both for the patient and in total. For the patient, the differential between amalgam and glass ionomer was small, but the total cost for amalgam was considerably lower than for either of the other two materials, except under the most extreme assumptions for median survival time of two years for both amalgam and glass ionomer. The authors noted that longevity alone was not the only consideration for patients, who were also concerned about aesthetics and perceived health risks.

Tobi et al (1999) provided an economic evaluation of the relative merits of amalgam and composite resin for replacement of existing class II amalgams. Costs were based on operator time, which was consistently longer for composites. Effectiveness was measured both by longevity - up to five years - and USPHS evaluation. All of the 73 re-restorations examined lasted the full five years without replacement, though two of the ten MO/DO molar composites were repaired. The simple conclusion was that on cost-effectiveness grounds, amalgam was the material of choice. This evaluation concurred in the view that if patient perception of aesthetics or health hazard were taken into account this might alter the balance. It was also noted that, with practice, treatment times for composites could be shortened, but not enough to match those for amalgam. Furthermore, removal time for failed composites was about 1.5 times the time needed for removing failed amalgams.

Kidd et al (1992) discussed risk assessment, preventive treatment, and the relative merits of repair versus replacement. They also covered the choice of materials, and noted that different restoration materials are used for different classes of cavity.

Comparison of different materials is the theme of many of the papers already cited, and it is an area particularly well suited to randomised controlled clinical trials, since it is the relative performance in matched groups of teeth, rather than absolute performance, which is under investigation.

Examples of such comparison studies can be found in Downer et al (1999), Jones et al (2000), van Dijken (1996), Jokstad et al (1994), Smales et al (1991b), Robinson (1971), Crabb (1981), Roulet (1997), Mair (1998), Cunningham et al (1990), Mjör (1981), Folwaczny et al (2001), Tyas and Burrow (2002) and Wilson et al (2002). Pimenta et al (1998) carried out an *in vitro* comparison study of five different amalgam combination restorations and a control, and concluded that adhesive amalgam is better than amalgam alone in inhibiting demineralisation.

Letzel et al (1997) used Kaplan-Meier charts and Cox-regression to compare the survival characteristics of different compositions of amalgam. After exclusion of the restorations placed by one exceptional operator, the analysis was based on a total of 3,119 restorations. Most alloys performed quite well for the first six years, but thereafter conventional zinc-free alloys deteriorated fastest. Amalgams with high copper content (>12%), and especially such amalgams with additional zinc content (>3%), performed much better.

Burke et al (1999) sought comparison information directly from clinicians – vocational dental practitioners and their trainers. Similarly, Mjör and Moorhead (1998) sought self-reported comparison information from clinicians in Florida.

The debate about whether glass ionomer inhibits secondary caries, possibly by the release of fluoride, has been taken up in studies by Mjör (1996) and Randall and Wilson (1999a).

The improvement in the performance of tooth coloured materials, and the possibly associated shift away from amalgam, were documented in Mjör

(1997), Deligeorgi et al (2001), Bogacki et al (2002), del Aguila et al (2002). The performance of a particular group of these materials, the compomers, was considered by Crisp and Burke (2000), Burke et al (2001), Blunck (2001), and Hickel and Folwaczny (2001).

2.7.2 Other Factors

Only a small group of papers considered other factors, such as patient age or attendance pattern, possibly because of the difficulty of extracting reliable information about the effects of such factors from relatively small sets of data.

Hawthorne and Smales (1997) considered the following factors in a life table survival analysis: dental practice, patient age, patient attendance pattern, change of dentist, experience of dentist, placement versus replacement. None of the factors proposed produced a consistently significant effect on survival, suggesting a complex pattern of associations, coupled with a paucity of data.

Boyd (1989) considered that failure of a filling had been attributed to three principal factors: the dentist, the materials, and the patient. She declared that great advances had happened in all three areas.

Jokstad et al (2001) set out a wide-ranging review of all factors affecting quality of dental restorations. They demonstrated variation between clinicians, in their technical skill, their perception, their judgement, and their attitude to risk. Later sections considered the factors which affect the quality of a dental restoration:

1. 'Form' (contours, textures and wear). These include materials, cavity design, finishing, and patient characteristics - intra oral location, gender and age, and the oral environment.

2. Optical properties, which include material factors, operator factors and patient factors.
3. Adaptation, which includes material factors, operator factors, cavity design, material handling, isolation, and patient factors, specifically intra oral location and oral environment.
4. General performance - material factors, operator, cavity design, material handling, isolation, patient factors inc patient attendance, and technical excellence.
5. Specific replacement reasons, including allergy, endodontic complications, material factors, operator factors, including cavity design and material handling, and patient factors such as intra oral location, age and gender, oral environment and technical excellence.
6. Periodontal problems - material factors, operator factors including cavity design and material handling, patient factors and technical excellence.
7. Aesthetics - material factors, operator factors including material handling, patient factors such as oral environment, and technical excellence.
8. Material deterioration - material factors, operator factors, cavity design, patient factors such as intra oral location and oral environment, and technical excellence.
9. Caries - material factors, operator factors, patient factors and technical excellence.
10. Tooth fracture - material factors, operator factors, patient factors and technical excellence.
11. Loss of restoration - material factors, operator factors, cavity design, isolation, patient factors (gender and age and oral environment) and technical excellence.

Bader and Shugars (1995b) noted in a literature review that variation could occur at all or any of the three stages of (a) diagnosis, (b) decision whether to intervene and (c) selection of treatment. Variation could be detected at level of practice (dentist), patient, or tooth. The three can interact, and the available literature was limited. Quantification of the variation is crude - using terms such as 'heterogeneous', 'striking', and 'marked variation', without any basis for answering the question "How much variation is too much?" However, across all levels, variation in dentistry is clearly substantial.

Some studies of tooth extraction reasons have taken account of patient and dentist characteristics – examples include Kay and Blinkhorn (1986) and Agerholm and Sidi (1988). Agerholm (2001) found that there was a strong relationship between patient age and extraction reason - orthodontics dominated for those aged up to 20, caries up till age 50, and periodontal reasons for the over fifties. Broad regional patterns were also noted - more extractions for caries in Wales and northern England, more orthodontic work in southern England and in the Midlands and East Anglia. Because of confounding between factors, single factor analysis in isolation can be difficult to interpret reliably.

Although not always isolated as a measurable factor, patient age is generally acknowledged as a contributory risk factor. York and Arthur (1993) reported that as patients get older, more restorations are placed for non-carious reasons than because of caries: for patients aged 35+ non-carious (eg fracture, endodontic) was a more common reason than caries. Contrary to other studies, Jokstad and Mjör (1991a) found a relation with age – survival was apparently worse in younger patients. Friedl et al (1994) divided their patients into groups according to age and dentition. Aalen et al (1995) considered patient age and sex as risk factors, but found neither to be significant. Fontana (1993) noted that type of patient, especially age, was related to the cause of restoration failure. Plasmans et al (1998) found that while there was no significant difference between their three operators or the five methods of retention, the age of the patient was significant, with older patients having poorer restoration survival.

Mjör et al (1990) concluded that longevity depends on material quality, operator proficiency, and the oral hygiene of the patient. Jokstad et al (1994) cited type and size of restoration, material used, and intra oral location as important factors. Kay et al (1996) reported failure rates according to tooth position. They also conducted an analysis of sub-populations, such as regular versus irregular attendees and periodontal attachment less than or greater than 4mm. The results were qualitatively in line with expectations. Drake (1988) distinguished between different tooth positions within the patient's mouth. Robbins and Summit (1988) found no significant difference according to tooth type or percentage cusp coverage. Clarkson et al (2000) documented the pattern of treatment, by age and tooth position. Lavelle (1976) concluded that most of the cross-sectional failures were attributable to dentist skill factors. Crabb (1981) noted that there was a systematic difference between hospital and general practice, expecting that there would be a higher drop-out rate among hospital patients who were satisfied with their treatment, compared with patients in the GDS.

Size of cavity has also been recognised as a risk factor. Elderton (1976a) concluded from a literature review that about a third of all restorations present at any one time may be considered to have failed for one reason or another. He debated the issue of cause and effect - poor carving versus caries. He also noted that 'Inadequate extension of the cavity' was the most frequently cited cause of failure. Maryniuk and Kaplan (1986) found that a classification by the number of tooth surfaces affected was useful. Sheldon and Treasure (1999) provided a useful checklist of objective (patient, tooth and operator or restoration) and subjective (incentives, patient preferences, treatment philosophy) effect modifying factors. Jokstad and Mjör (1991b) attempted to relate replacement and longevity to cavity design. They used linear discriminant analysis to predict response, in this case success or failure of a restoration for a specific reason. Factors, including those relating to cavity design, were included stepwise.

Bogacki et al (2002) had sufficient data to attempt to model a range of risk factors. Cox regression, using SAS, was used to test the associations of restoration longevity with the following predictor variables: patient sex, age, dentist age, tooth location, prior restorative history (number of restorations in year prior to restoration), year of treatment, change of dentist (defined as change of dentist between index restoration and replacement), and restoration material type. All predictor variables other than patient sex were statistically significant.

2.8 Statistical Methods

Apart from the use of simple descriptive statistics to describe the distributions of completed restoration lives in cross-sectional studies, there are three main techniques in common use for the empirical investigation of survival behaviour: life tables, Kaplan-Meier, and Cox regression. All these three techniques are described in Collett (1994). At least one of the studies in this review has used Collett as a reference work - Qvist et al (1997). Although the methods described in the dental literature for cross-sectional analysis are uncomplicated, there is a more extensive demographic literature concerned with human populations which describes more sensitive techniques.

2.8.1 Life Table

The life table or actuarial method groups the observations into time intervals, ignoring the re-intervention or censoring times within those intervals. The hazard function for that interval is calculated as the average ‘death rate’ over the interval, using the number of cases present at the beginning of the time period and the numbers retreated or censored within the period.

Examples of the use of this method include Elderton (1983b), Patterson (1984), Jokstad and Mjör (1991a), Smales (1991), Smales and Hawthorne (1997), Robbins and Summit (1988), and Hawthorne and Smales (1997). Davies (1987) provided a critique of the method in the context of dental restorations.

2.8.2 Kaplan-Meier

The Kaplan-Meier or product-limit technique is an extension of the life-table method to individual retreatment times. Strictly, it produces a step function for the cumulative survival curve, with zero hazard between retreatment times.

Kaplan-Meier is probably the most widely used technique, not least because it is readily available in statistical packages such as SAS and SPSS. It also requires minimal pre-processing of individual case records, and avoids the loss of information inherent in the interval-grouping of the actuarial method.

Before considering how it can be modified, it is useful to review the original Kaplan-Meier method of analysis. This method is a well known and versatile way of estimating the empirical survival function. It is well expounded by Collett

(1994). The method has been described as a product-limit estimate. It consists of a series of point estimates at the times at which the event of interest occurs. The resulting cumulative survivor function is a step function with steps at the death times and constant between them. The size of each step, relative to the current value of the survivor function, is calculated by dividing the number of deaths by the number of cases ‘at risk’ at the date of death. This method of calculation can be justified provided that the deaths can be regarded as occurring independently of one another.

The Kaplan-Meier method permits the use of censored data – so that all cases exposed to risk can be included. However, it is important to check that censored cases are not informatively censored – a censored case should have the same expectation of survival at the time of censoring as an uncensored case.

The classical setting for a Kaplan-Meier estimation of a survival curve is a prospective clinical trial where regular checks are made on the subjects of the research and ‘drop-out’ occurs through factors which are clearly unrelated to the subject of the research – such as patients leaving the study area for unrelated domestic reasons.

In the case of a retrospective set of attendance records, as in the present study, there is a more challenging task, since there are generally no reliable information sources which can confirm the reason for non-attendance. ‘Non-attendance’ includes cases where a change in recording personal details results in a break in the chain of successive matched records, in addition to cases where the patient has not physically attended. There may also be cases where some intermediate records have been misclassified: for example, where a patient attends another dentist for occasional treatment in an emergency away from home. One of the biggest problems is to decide whether a patient who has not attended for a specified period of time is still part of the population at risk. This problem was noted by Davies (1987), but she did not propose any systematic method of solving it. The second question, if the answer to the first is to any extent negative, is when did the patient leave the population. Only when these two questions have been satisfactorily answered can an attempt be made to bring such techniques as Kaplan-Meier to bear on such data.

Examples of the use of Kaplan-Meier can be found in Hujoel et al (1998), El-Mowafy et al (1994), Drake (1988), Strand et al (2000), Folwaczny et al (2001), Roulet (1997), Plasmans et al (1998) and Fradeani and Redemagni (2002). Scherrer et al (2001) provided a good account of the use of the technique for studying the survival of all-ceramic crown systems.

Even when more elaborate models, such as Cox regression or Frailty are under consideration, a Kaplan Meier analysis is normally carried out first to establish the empirical raw distributions with allowance for censoring.

However, it is important to have sufficient data if clinically significant effects are to be detected with statistical significance. Chadwick et al (2001b) conducted a retrospective examination of the records of glass ionomer restorations placed by senior dental students between 1992 and 1998. The choice of whether to treat dentine with polyacrylic acid was made by the supervising staff member. Those records where complete follow-up was available were included in the study - a total of 149 restorations, of which 48 had received the cleansing treatment. Kaplan-Meier charts were drawn, suggesting better survival for those restorations treated with the cleanser. However, a Log-Rank test did not detect a significant difference, even though the hazard ratio was estimated at 1.49. The obvious conclusion is that the data were too few to achieve sufficient power to detect a clinically significant effect.

2.8.3 Cox Regression

The Cox Regression or Proportional Hazards technique is a semi-parametric method of incorporating risk factors into an empirical survival curve. Instead of simply plotting different survival curves for different subgroups of the experimental population, a Cox Regression analysis works on the assumption that the hazard functions for different subgroups bear a constant ratio to one another. Provided of course that this assumption is reasonable, this method enables the analyst to interpret the effects of different risk factors in an intuitively accessible way.

Cox (1972) described the development of the method in the light of existing techniques such as Kaplan Meier and life tables. Examples of the method as used on dental restorations include Hujoel et al (1998), Dunstan et al (2000), and Bogacki et al (2002).

2.8.4 Cross-sectional Techniques

Three main techniques can be found in the demographic literature, each appropriate to the extent to which intervention and *in situ* data are available at the cross-sectional time. These methods are all developed from first principles in section 3.3.1.

Where intervention data alone are available, then a technique similar to that used in the dental literature was described by Ní Bhrolcháin (1987), and also by Feeney and Yu (1987).

Where *in situ* data alone are available, then the ‘current status’ estimator is widely used in demography – a description may be found in Diamond and McDonald (1992).

Finally, when both intervention and *in situ* data are available, the Nelson-Aalen estimator (equation (iii) in section 3.3.1) is appropriate. The method is described in Anderson and Væth (1988).

2.8.5 Weibull and Other Models

Whichever of the above methods is used to derive the empirical survivor function, it is possible to devise explicit functions to fit a smoothed version of it. In particular, a function from the Weibull family of curves has certain very attractive properties which encourage its use for survival analysis. In particular, it has the ‘proportional hazard’ property that the cumulative survivor function of a population with a hazard function proportional to that of a Weibull distribution is itself a Weibull function.

A further attraction of a fully parametric model is that it enables the analyst to project the survival curve beyond the time period that has actually been observed. Subject as always to the proviso that the model should be clearly appropriate to the data, parametric models can generally produce estimates to a greater precision, expressed in the form of confidence intervals and significance tests, than corresponding non-parametric or semi-parametric models.

Examples of the use of a Weibull regression model for dental restorations can be found in Smales et al (1991a), Smales et al (1991b), Geurtsen and Schoeler (1997), and Scherrer et al (2001). Kay et al (1996) proposed assuming an exponential distribution for the life of a tooth. An exponential is a member of the family of Weibull curves, so if tenable, this characterisation of tooth life would be more readily used by patients and dentists in decision-making and assessing the clinical effectiveness of treatment.

Mention should also be made of Frailty models. Such a model assumes that within the groupings of the population there is an underlying individual ‘frailty’ factor such that each individual has a different survivor function. Aalen et al (1995) provided a demonstration of the use of a frailty model to describe the observed survival behaviour of amalgam fillings in a sample of 32 patients from seven dentists in Oslo. Data covered all fillings placed in the period 1970 to 1987, on 'facial, oral, mesial and distal surfaces on all premolars and first and second molars'. Empirical cumulative hazards ('intensity') plots were produced for individual patients. These were combined into a mean survival curve, weighting by patient. This was similar to the usual empirical survival curve, weighted by filling.

The variation between patients was then explored by using a frailty model with an underlying Weibull distribution, and estimating parameters by maximum likelihood. Individual frailties were estimated by a Bayesian method, and the model was extended by assuming a proportional hazards model with two covariates: sex and age (over or under 50).

An alternative way of modelling the hierarchical clustering of frailty is a technique known as multi-level modelling. Gilthorpe et al (2002) applied this method, using an underlying proportional hazards model, to the records of 200 RAF personnel. The multi-level model took account of the hierarchy of successive restorations within tooth, and different teeth within patient. Because single level modelling ignores these effects, the authors argue that confidence intervals based on such modelling are too narrow. The alternative of using just one restoration from each patient introduces bias and severe loss of precision. The underlying median survival times were estimated at 11.5 years for the single level model and 12.5 years for the multi-level model.

2.9 Summary

This review has summarised the literature over the past thirty years concerning the life of directly placed restorations. It has dealt with the issues concerned with definition and measurement of the start and end of the life of a restoration. It has considered the debates about what methodology is appropriate – and in particular the relative merits of cross-sectional practice-based studies as compared with randomised controlled prospective clinical trials, generally under the aegis of a school of dentistry.

The reasons why restorations are placed or replaced, or come to an end in other ways, have been explored, and the variability of clinical opinion, particularly on whether secondary caries is present, has been demonstrated.

The empirical findings in the literature on the median and five, ten, and twenty-year survival rates have been documented – estimates of median survival are generally around ten years, varying up or down according to the materials and population. Factors thought to affect survival include materials, size of cavity, and patient and operator characteristics, but few studies have been sufficiently large to detect significant differences.

Finally, the statistical methods in use have been reviewed. These range from simple descriptive statistics based on life at replacement for cross-sectional studies to parametric and semi-parametric models using longitudinal data and explicitly incorporating a range of risk factors.

3 MATERIALS AND METHODS

3.1 The Data Sources

The data source for all three of the activity data sets was the same: the records of item-of-service claims passed for payment by the Dental Practice Board (DPB). In order to receive NHS payment, dentists working in the General Dental Services (GDS) were required to submit claims in respect of every patient they treated under the NHS. The DPB had a service level agreement with the Department of Health (DoH) to process these claims within tight limits around thirty days from receipt at the DPB to delivery into the dentist's bank account. There was thus a considerable internal pressure in the system to ensure accurate and timely production of data.

The underlying structure of these records is a nested sequence of sub-records for each course of treatment, with mixed record types at the level of nesting below that of course of treatment. The master record contains information about the dentist, the patient, and the course of treatment as a whole. Each master record is accompanied by one or more sub-records, each of which contains information about a specific type of treatment claimed within the course of treatment. Depending on the type of treatment, some of these treatment records are in turn accompanied by sub-records, one or more for each of the mouth quadrants within which at least one tooth has been treated with that treatment. The quadrant record consists of a string of numbers and letters, each indicating a treatment applied to a specific tooth position.

The original home of the data was to be found on an operational scheduling and payment system running with COBOL programs on an IDMSX database under the ICL VME operating system. From this system a binary file known as ‘schedrec’ was generated, and this was the underlying vehicle for the activity data used in this thesis. A subset of schedrec data, restricted to patients with specified dates of birth, together with certain additional derived fields, was also generated. This has been produced since 1990, and forms the basis of the longitudinal dataset. Since 1990 there have been various changes to the file formats, and the subsequent data organisation programs have taken these changes into account.

The schedrec files have been retained since October 1997, and have been routinely converted from their original binary and EBCDIC form into ASCII character form, and restructured onto a RedBrick database on a Windows NT server, with access via SQL generated by a commercial software package known as ‘Designer’. The longitudinal data files have been converted to ASCII format using a bespoke parameter-driven COBOL conversion program, then transferred and read into flat rectangular files on a local PC. Subsequent processing was carried out using the statistical analysis package SPSS, supplemented by Microsoft Excel for presentation of charts and tables.

3.1.1 The Early Life Data

The early life data consist of all tooth treatment records scheduled for payment between March 2000 and March 2001, inclusive, for patients born in any of the years 1935, 1945, 1955, 1965, and 1975. The DPB’s database covers all GDS treatment provided throughout England and Wales.

The variables extracted were as follows:

Surname Patient surname

Initial Patient first initial

Sex Patient sex (‘M’ or ‘F’)

Dobirth Patient date of birth

Dorec Date when claim was received by DPB

Schednum Schedule number – year and month in which the payment schedule was created

Fpcnum The first part (of four parts) of the dentist’s GDS contract number, relating to the health authority in which the surgery was located

Persnum The second part, containing the dentist’s personal number - as issued by the DPB

Partnum The third part – the reference number for an existing partnership, or zero if there is none

Suffix The final part of the contract reference number

Postcode The patient’s home postcode

Doacc Date of acceptance – in most cases the start of the course of treatment

Docomp Date of completion – in most cases the day when the course of treatment comes to an end, but sometimes this field is empty, because the patient did not return to complete the course of treatment

Exempbox A categorical variable indicating, for those patients who were excused from paying full patient charges, the reason for exemption or remission

Trtcode A four digit code indicating a treatment item from the Statement of Dental Remuneration (SDR), as listed by Department of Health (2002)

Quadrant A symbolic code (#,%,& and ‘), corresponding to Upper Right, Upper Left, Lower Right and Lower Left, as seen from the patient’s viewpoint

Toothpat A nine-character string containing digits (1 to 8) indicating permanent tooth positions and letters (A to E) representing deciduous tooth positions, and ‘S’ to represent supernumerary tooth positions

Guarant An indicator variable (value ‘G’) to show whether the dentist had provided that particular treatment under guarantee (and therefore had made no charge to the patient)

Complted An indicator variable to show whether the course of treatment had been completed (and so had a completion date – see **Docomp** above).

The data records actually used in the analysis were restricted as follows:

For the records scheduled in March 2000 the treatment records for individual teeth were restricted to those which included at least one of the following six standard direct restoration treatment items:

Item 1401: single surface amalgam

Item 1402: two surface amalgam, not MO or DO

Item 1403: MO or DO amalgam

Item 1404: MOD amalgam

Item 1421: Composite resin or synthetic resin, including acid etch retention

Item 1426: Glass ionomer, silicate or silico-phosphate

Where additional treatments related to the restoration were provided, specifically items 1422 to 1424 for incisal angles and edges, 1425 for cusp tips and 1431 for pin retention, then this was retained in a supplementary variable. Another supplementary variable was used to record whether the restoration had been provided under the NHS twelve month guarantee of free replacement. Where more than one type of treatment (within the above restricted range) was placed on the same tooth at the same date a combination code (**addtrt**) was generated by concatenating the codes.

Deciduous and supernumerary teeth were ignored and the records were expanded to tooth level – one record for each treatment on each tooth – retaining additionally all the information about the course of treatment in which the treatment was provided.

For the remainder of the records, no restriction was placed on the type of treatment, but only records where the same tooth had been treated in March 2000 were retained. Cases from the year ending March 2001 where the date of acceptance was the same for both courses of treatment were merged, and the most recently received details used, on the grounds that they were likely to be correction records, replacing the original course of treatment.

The combined file was then reduced further, to include only the treatments provided on the first re-intervention on the tooth, and ignoring additional fee items. A flag variable (**failguar**) was also created to show whether any of the replacement restorations had been provided under guarantee.

The time interval in days between the date of placement (date of completion if present, date of acceptance otherwise) of the first course of treatment and the date of acceptance of the second was calculated. Where there was no further course of treatment in the schedule year ending March 2001, or where the interval was outside the range [1,365] days, the time interval was set to 'missing', and the data was treated as censored at 365 days. This could happen if the next course started more than 365 days later than that processed in March 2000, or the other course actually started earlier, but was processed later.

The resulting file therefore contained a record for each directly placed restoration (within the specified range of SDR codes) provided to patients of the specified year of birth, showing the time interval in days from treatment to next treatment for those teeth which were retreated within a year, together with classification variables for both the original restoration and the subsequent treatment, if any.

3.1.2 The Cross-sectional Data

The source data for the cross-sectional analysis consist of the records of all teeth treated during the thirteen months ending on April 30th 2001 for GDS patients who were born in the year 1965. Using methods similar to those used for the ‘early life’ dataset, above, a set of restoration ‘lives’ was derived, each record containing the date on which a filling was placed and the date, if any, on which the same tooth was next treated with a treatment which implies that the original filling is likely to have been replaced or removed. These treatments comprise further fillings, crowns and extractions, but not stoning and smoothing, which imply that the filling remained in place.

The same initial set of variables (as in 3.1.1) was extracted for each case, though no restriction was placed on the records to be included. It should be noted though that the data were defined by the dates of acceptance (from April 1999 to April 2001) and dates of completion (from April 2000 to April 2001), not the dates of scheduling, and so take advantage of the subsequent schedules to include claims subject to late submission or processing, while filtering out claims which related to courses of treatment completed prior to April 2000. The data file was extracted from the database in January 2002, allowing at least eight months for claims to be submitted.

Three sets of derived aggregate data were created from this initial data set, for each time interval from 1 to 365 days before a date in April 2001:

a) The number of restorations originally provided that number of days previously
b) The number of restorations remaining *in situ*, having been provided that number of days previously
c) The number of teeth retreated, having last been treated that number of days previously

This exercise was carried out both for the totality of directly placed restorations (as defined in 3.1.1), and grouped by treatment code.

Aggregate a) involves totalling the number of restorations by date and aggregating over the thirty days corresponding to the thirty day cross-sectional period in April 2001.

Aggregate b) involves removing from aggregate a) any cases which have, before the corresponding date in April 2001, received further treatment which implies that no filling should remain *in situ* on that date, namely crown, extraction or bridge.

Aggregate c) involves determining for each tooth treatment placed in April 2001 whether the tooth was the subject of previous restoration within the last 365 days, and if so, when the most recent restoration was placed.

For efficiency of computation, SPSS macros were written and used to generate these files of aggregate totals.

3.1.3 The Full Longitudinal Data

Although the full longitudinal dataset has the same origins as the other two, it goes back much further, and is based on a sample of patients, determined by their dates of birth.

The sample birth dates were chosen at the rate of twenty for each year of birth, with a cycle recurring each century. Within each year, the twenty were chosen on a pseudo-random basis, and twenty sub-samples, each containing one date in each year, were further defined. The main data source for this research comprises the treatment data generated by one such sub-sample, with a second to be used for replication of the analyses. The data for the main longitudinal dataset come from sub-sample number 11.

The reason for choosing the sample in this way, rather than drawing a new simple random sample afresh each time, is primarily to allow the same patients to reappear in the sample data every time they attend a GDS dentist. By stratifying the sample across years of birth, the sample structurally reflects the age distribution of the total population of the GDS, another advantage over a simple random sample, given that there are reasons to expect patterns of treatment to change with age (eg the life-time progression from virgin teeth to edentulousness).

Although the data can be, and are, processed on a month by month basis to provide detailed aggregations of current activity, they can be re-ordered to give, for each patient separately identifiable within the sample, a longitudinal set of data chronicling the pattern of treatment that that patient has received over many years.

The source set itself consists of a collection of monthly files, each containing all the records for the sample which have been ‘processed’ during a month. In this case the process consists of gathering together all the validated item of service course of treatment records for a particular dental ‘contract’ in order to produce a payment schedule for the specified month. The more technical items in the above terminology are explained in the glossary. For operational reasons, processing is spread across up to twenty different days in each month, and the actual date of processing may in fact fall outside the nominal ‘schedule month’.

Because of the time lags between starting and ending a course of treatment, and between completing, or abandoning, a course of treatment and sending the data to the DPB, plus the time taken between receipt and scheduling at the DPB, it may be several months after the start of a course of treatment before the course of treatment appears in the longitudinal data.

A further operational consideration is the method used for retrospective correction of errors. Once a claim has been scheduled, any change, for example the late addition of a treatment code that had been omitted, will involve creating two new records. The first consists of a deletion record, with the same course of treatment data except that the fees values are made negative. Deletion records are not accompanied by records showing the treatment which has been deleted. The deletion record is followed by a correction record, which consists of the records as they should have been originally, including treatment records.

A description of the structure of the file may make the above a bit clearer. The Statement of Dental Remuneration (Department of Health, 2002) contains a comprehensive list of the codes of all the treatment items to which reference is made in this research. Every course of treatment initially generates one course of treatment record, accompanied by one or more treatment records. Further records may subsequently be generated, both for courses of treatment and for individual treatments, in order to carry out retrospective corrections.

The course of treatment record provides identification of the dentist and of the patient (or at least, surname, first initial, sex and date of birth), various dates related to the course of treatment (acceptance, examination, completion), and a range of markers and comments relating to patient exemption status and the way in which it was processed at the DPB. The course of treatment record also contains details of the total item of service fees, patient charges, and the fee scale on which the payments were calculated.

Treatment records are of three types: basic, general, and tooth-specific. Basic treatment consists of either a simple examination and report or a simple scaling. A basic treatment record consists simply of a symbolic code.

A general treatment record comprises a treatment code, a quantity, indicating the number of such treatments provided during the course of treatment, and an amount, indicating the total scale fees for that item of treatment. As an example, consider code 0201, small radiograph. The quantity shows the number of small radiograph films claimed, and the amount the fees corresponding to that quantity of small radiographs, as laid down in the SDR scale of fees current at the date of acceptance.

A tooth treatment record contains treatment code, amount, and a tooth notation, indicating which teeth have been treated under that code. There is also a guarantee indicator (another feature introduced by the 1990 New Contract) to show whether the treatment has had patient charges waived because it involves the replacement of a restoration which has failed within twelve months of provision. Filling treatment records are of this type.

Although the data structure is essentially the same as for the other datasets, special programs had to be written to translate the data into similar final format. The variables extracted were as follows:

Schednum A five digit number indicating the year and month of the schedule on which the claim was processed

Fpcnum The first part (of four) of the dentist's GDS contract number, relating to the health authority in which the surgery was located

Persnum The second part, containing the dentist's personal number - as issued by the DPB

Partnum The third part – the reference number for an existing partnership, or zero if there is none

Suffix The final part of the contract reference number

Patname Patient surname

Patini Patient first initial

Patsex Patient sex (‘M’ or ‘F’)

Patdobn Patient date of birth – in a coded integer form

Doacc Date of acceptance – in most cases the start of the course of treatment

Doexam Date of examination – the date on which the patient was examined, generally on after the date of acceptance, and on or before the date of completion

Docomp Date of completion – in most cases the day when the course of treatment comes to an end, but sometimes this field is empty, because the patient did not return to complete the course of treatment

Exempbox A categorical variable indicating, for those patients who were excused from paying full patient charges, the reason for exemption or remission

Scalfees The total fees payable under the then current scale for all the treatment on the course of treatment, excluding ‘scale additions’ in respect of claims submitted long after the date of acceptance (in practice, scale additions apply mostly to orthodontic courses of treatment for children, so are of little relevance to this research)

Remismkr An alternative indicator that the patient was excused from having to pay full patient charges, by reason of full or partial remission

Doprocn Date of processing, expressed as the number of days since January 1st 1900 (inclusive)

Patpost The patient’s home postcode – frequently missing or incomplete for records relating to the early years

Patage The age of the patient in years at the date of acceptance – an error in the creation of the original file calculated this variable incorrectly, so it was recalculated from the date of birth and date of acceptance within SPSS.

Trtcode A four digit code indicating a treatment item from the Statement of Dental Remuneration (SDR), as listed by Department of Health (2002)

Quant Number of instances of the treatment item, where the item is not tooth-specific (eg number of small radiographs, item 0201)

Guarant An indicator variable (value 'G') to show whether the dentist had provided that particular treatment under guarantee (and therefore had made no charge to the patient

Count The number of quadrants records associated with this treatment – in practice, almost invariably four or fewer

Toothpat The full pattern of tooth positions treated (40 characters long) containing a concatenation of the first four quadrant records, together with their quadrant symbols

Claimidn A unique claim reference number (within this subsample) generated by combining the schedule reference number (month and year) with the position of the claim in the sequence of claims processed on that schedule.

The monthly files from which these data have been extracted go back to the January 1991 schedule, and extend forward to the March 2002 schedule. Any claim with a date of acceptance on or after 1st January 1991 cannot appear on an earlier schedule, and most of the claims with dates of completion on or before 31st December 2001 are likely to appear on or before the March 2001 schedule.

The course of treatment data were merged into a single file and restricted to patients aged 18 or over at the date of acceptance. Having assembled the course of treatment data for the longitudinal dataset, various further datasets were created.

In particular, a file was created containing all the patient identities (defined as unique combinations of surname, initial, sex and date of birth), supplemented with information derived from the course of treatment data, such as the date when the patient last attended a GDS dentist (based on the most recent date of acceptance, examination, or completion), both overall and within each year. A unique patient ID number was also created, to simplify further processing (eg sorting). A sub-file was created consisting only of those who, at some time in the longitudinal period (January 1991 to December 2001), had received at least one directly placed restoration. The file of course of treatment data was then further restricted to records for patients in this subfile.

Treatment codes for ‘occasional’ treatments (where the patient is not registered with the dentist providing the treatment) were then converted into the standard codes used in the early life and cross-sectional analyses. Specifically, codes 5811, 5812, 5813, 5814, 5821 and 5826 were recoded as 1401, 1402, 1403, 1404, 1421 and 1426 respectively. Variables were also created to describe the associated treatment on the same tooth and in the same course of treatment, and the next treatment affecting that same tooth. Time in days from restoration to next intervention on the same tooth, or 31st December 2001 was calculated, and an indicator created to show whether a re-intervention had occurred.

A further analysis was carried out of the pattern of attendance of each patient over the course of the observation period, and appropriate indicators added to the file of patient records.

Finally, after the analyses and adjustments described in section 3.4 had been completed, the dataset was merged with other data related to dentist or geography (3.1.4), and all variables were appropriately labelled and formatted. The final set of variables is as follows:

patidn	Patient ID number
quadrant	Mouth quadrant
tooth	Tooth position
claimidn	Claim ID number
lastvn	Last date of visit by patient (days)
doplacn	Date of placement (days)
interval	Interval to March 02 schedule (months)
maintrt	Main treatment
filled	Tooth filled?
additrt	Additional filling treatments (sum of codes)
pinscrew	Pin or screw retention (indicator)
amalgam	Amalgam filling on this tooth
comp	Composite resin filling on this tooth
glassion	Glass ionomer filling on this tooth
root	Root treatment on this tooth
veneer	Porcelain veneer on this tooth
inlay	Inlay on this tooth
crown	Crown on this tooth
bridge	Bridge on this tooth
extract	Extraction of this tooth
denture	Denture on this tooth position
time	Time to re-intervention

reptreat	Next treatment on tooth
nexclaim	Claim ID for next treatment on tooth
nadditrt	Next additional filling treatments (sum of codes)
npinscre	Pin or screw on next
namalgam	Amalgam on next
ncomp	Composite resin on next
nglassio	Glass ionomer on next
nroot	Root treatment on next
nveneer	Porcelain veneer on next
ninlay	Inlay on next
ncrown	Crown on next
nbridge	Bridge on next
nextract	Extraction on next
ndenture	Denture on next
exempbox	Exemption/Remission code
dentsex	Sex of dentist
dentyob	Year of birth of dentist
yearqual	Year of qualification of dentist
postarea	Postcode area
region	Region
fluoride	Fluoridation status
dentstat	Dentist status

counqual Country of dentist qualification

chgepay Charge-paying status

chandent Number of subsequent changes of dentist

chanpay Number of subsequent changes in charge-paying status

subscls Number of subsequent claims

patage Patient age

aexam Associated exam

arads Associated radiographs

aperio Associated periodontal treatment

aamalgam Associated amalgam

acomp Associated composite resin

aglassio Associated glass ionomer

aroot Associated root treatment

aveneer Associated porcelain veneer

ainlay Associated inlay

acrown Associated crown

abridge Associated bridge

aextract Associated extraction

adenture Associated denture

asedatio Associated sedation or GA

adomvis Associated domiciliary visit

arecatt Associated recalled attendance

patsex	Patient sex
maxint	Maximum interval between courses
medint	Median interval between courses
meanint	Mean interval between courses
numclam	Number of claims for patient
totfees	Total fees claimed
meanannf	Mean annual fees claimed
yearplac	Year of restoration placement
reint	Re-intervention flag
caseid	Case ID (for time-dependent censor adjustment)
prreatt	Estimated probability of re-attendance
recid	Record ID (for time-dependent censor adjustment)
weight	Weighting (for time-dependent censor adjustment).
dentexp	Dentist experience (years)
dentage	Dentist age (years)
patagegr	Patient age (years)
chdentgr	Change of dentist
chpaygr	Change of charge-paying
intgrp	Median interval between courses
feesgrp	Mean annual gross fees.

3.1.4 Supplementary DPB Data

The contract number associated with each course of treatment was used as a link to other information held by the DPB about that dental contract, namely classification data about the dentist and geographical information about the surgery.

Specifically, from the dentist's date of birth and year of qualification, the age of the dentist and the number of years of post-qualification experience were derived. The dentist's country of qualification was also extracted, and grouped appropriately. From the type of contract, the status of the operating dentist, as principal, assistant or vocational dental practitioner (known as VDPs - recently qualified dentists undergoing a year of supervised practical experience).

3.1.5 Other Supplementary Data

By using surgery postcode, links can be made to other published data. Maps of fluoride concentrations were obtained from the Department for the Environment, Food and Rural Affairs (DEFRA) and postcode areas assigned by eye to a look-up table. The postcode was also used to allocate surgeries to broad regional geographic groups.

3.2 Methodology For Early Life Analysis

The statistical analyses took two forms:

- **Comparison tables and charts showing the proportion of uncensored cases (those retreated within 365 days) and**
- **Kaplan-Meier curves to show the distribution of times to re-intervention on the same tooth**

Tables were prepared for each of the eight tooth positions, showing cross-tabulations between mouth quadrant, type of original (March 2000) restoration, and patient sex.

A further analysis, restricted to those cases which had re-interventions, showed the distribution of re-intervention treatments cross-tabulated against the original treatments. A similar analysis showed whether the dentist who re-intervened was the same as the dentist who had provided the original treatment.

Kaplan-Meier curves were plotted to compare the cumulative survival curves (where survival time is defined as time to re-intervention) for the six types of original treatment, both across all teeth and separately for each tooth position. Log Rank tests were used to test the pair-wise differences between the curves.

As a control analysis, the times to first treatment of the teeth in the same position but different quadrants in the same patient, were used as an indicator of the expected survival time without treatment. These times were analysed by tabulation and Kaplan-Meier in a similar way to the main analysis of teeth treated in March 2000.

A supplementary tabulation and Kaplan-Meier analysis was carried out on the incisor teeth (positions 1 and 2) to assess the effect of additional treatment for class IV cavities. A similar analysis, for all tooth positions, assessed the extent to which there was proportionately more early re-intervention on restorations which involved the use of dentine pins (additional treatment code 1431), or restoration of cusp tips (1425).

Two further variables were investigated in their association with subsequent re-intervention: the guarantee indicator and whether the patient was eligible for free treatment. Because the guarantee is needed only if the patient has to pay patient charges, the analysis of the guarantee indicator was restricted to those patients who had to pay for the original course of treatment. In this case those teeth which had re-intervention without invoking the guarantee were treated as censored on the date when they received re-intervention. Kaplan-Meier curves were drawn for comparing charge-payers and non-payers for each of the six treatment types, and for comparing the six types within the re-interventions provided under guarantee.

The whole analysis was then repeated for the four other age groups.

A supplementary analysis was carried out on root fillings (code 1501) for patients born in 1965, using the same methodology, but expanding the 'additional treatments' to include those which may accompany a root treatment, such as crowns, inlays and bridges.

3.3 Methodology for Cross-sectional Analysis

In this section three alternative methods of inference from cross-sectional data are developed and compared, both with one another and with a conventional Kaplan-Meier analysis.

The aggregate data file derived in section 3.1.2 provides, under controlled conditions, three sets of information which might be available to a dentist when he examines his own patients or sets of dental records:

- **A set of restorations with re-intervention during the cross-sectional period, together with their age at re-intervention and the number of restorations placed at the same time as each restoration which had re-intervention**
- **For each day during the cross-sectional period, a set of restorations *in situ,* together with the age of each such restoration and the number of restorations originally placed at the same time**
- **For each day during the cross-sectional period, the set of restorations with re-intervention on that day together with the number of restorations *in situ*.**

Each of these sets of data is sufficient to produce an estimate of the survivor function for all values of time interval from 1 to 365 days.

The theory for each day of the cross-sectional period is described in the following sections. The term 'failure' is used as short-hand to indicate a re-intervention on a previously restored tooth.

3.3.1 Estimation of the Survivor Function

Let $f(t)$ be the probability density function for the continuous random variable *t*, the time to failure of a particular filling. The cumulative probability distribution function $F(t)$ denotes the probability that a filling fails at some time before *t* units of time. The survival function will then be $S(T) = 1 - F(T) = 1 - \int_0^T f(t)dt$.

The ratio $\frac{d_i}{r_i}$ will provide an estimate of $\int_{i-1}^{i} f(t)dt$ and hence an estimate of $S(T)$ will be

$$\hat{S}_1(T) = 1 - \sum_{i=1}^{T} \frac{d_i}{r_i} \text{ ....(i)}$$

An alternative approach is to use instead the records of restorations still present at the time of cross-section, drawn from the same administrative source as those for restorations which have failed, and the same data source for a volume indicator. It is then possible to record, out of the number r_i of fillings placed at time *i* prior to cross section time, the number s_i still in place at cross section time. This extra processing of records then enables a direct estimate of $S(T)$, the survivor function, namely

$$\hat{S}_2(T) = \frac{s_T}{r_T} \text{ ....(ii)}$$

Note that $d_i + s_i \le r_i$ as some fillings placed at time $t = i$ will fail before the cross section time.

However with this method there is no guarantee that the estimated survival function $\hat{S}(T)$ will be a monotonically decreasing function of *T* and some additional smoothing method which ensures monotonicity may be desirable.

Finally, if we have records both of the failures at time $t = 0$ and of the surviving fillings at that time, then we can estimate the age-specific death rate, or hazard function $h(i)$, directly by

$$\hat{h}(i) = \frac{d_i}{s_i}$$

Hence the cumulative hazard function $H(i)$ can be estimated by

$$\hat{H}(i) = \sum_{j=1}^{i} \frac{d_j}{s_j}$$

and hence the cumulative survival function $S(T)$ can be estimated as $\exp(-H(T))$, that is

$$\hat{S}_3(T) = \exp\left(-\sum_{j=1}^{T} \frac{d_j}{s_j}\right) \text{...(iii)}$$

A natural extension of these methods involves repeating the estimation functions above using successive points of time=0, 1, 2, ..., n as the cross-section time. The variation in the size of the denominators in equations (i) to (iii) can be compensated for by using the ratio of sums, rather than the average of ratios. The resulting cumulative survival function estimates are then as follows.

$$\hat{S}_4(T) = 1 - \sum_{i=1}^{T} \frac{\sum_{j=0}^{n} d_{i+j}}{\sum_{j=0}^{n} r_{i+j}} \text{...(iv)}$$

$$\hat{S}_5(T) = \frac{\sum_{i=T}^{T+n} s_i}{\sum_{i=T}^{T+n} r_i} \text{...(v)}$$

$$\hat{S}_6(T) = \exp\left(-\sum_{j=1}^{T} \frac{\sum_{i=j}^{n+j} d_i}{\sum_{i=j}^{n+j} s_i}\right) \text{...(vi)}$$

It is these last three formulae, together with Kaplan-Meier analysis of the complete thirteen-month data set, with censoring at 365 days, which form the basis of the cross-sectional analysis. Approximate standard errors for these estimates can be found in the demographic literature, but the purpose here is simply to demonstrate that all three methods provide an acceptable alternative to Kaplan-Meier analysis where the full dataset is not available. What is more, the third method (the Nelson-Aalen estimator) does not require any information beyond that which is clinically necessary to be available at the time when, during the cross-sectional period, the patient is examined.

3.3.2 Implementation of the Theory

The Kaplan-Meier analysis involves standard application of SPSS software, as for the early life analysis. The essential difference here is that the data consist of all restorations placed over a thirteen month period, and that censoring occurs at the end of that period or at 365 days, whichever occurs earlier.

The cross-sectional analyses themselves were carried out using custom written Excel spreadsheets, deriving the intermediate components of the formulae in section 3.3.1, and then plotting the resulting cumulative survival curves for all three methods, compared against the Kaplan-Meier analysis.

3.4 Methodology for Full Longitudinal Analysis

In this section a method is derived for overcoming a fundamental limitation on attempting to use unmodified Kaplan-Meier estimates, namely the fact that in a limited observational study of this kind the date of censoring, except if it occurs at the end of the observation period, is never known. Because the theory has been developed specifically by the author in the light of empirical findings about this particular longitudinal dataset, some auxiliary tables have been included in the results chapter (section 4.3.2), both to illustrate the method and to justify the direction taken in developing the methodology. The rationale for the method used may be found in section 5.1.

3.4.1 Observation Bias – Whether to Censor

A method has been devised for systematically adjusting the estimate of the number of ‘at risk’ patients by introducing an empirical function relating the estimated probability of re-attendance to the time interval in months between the last recorded attendance of the patient and the last payment schedule from which data were available.

The data in the DPB dataset consist of a hierarchically structured set of records, nested within a basic record for the course of treatment – essentially, all the treatment contained within one claim ‘form’ (whether paper or electronic). On one such claim record, there may be many sub-records, relating to several different treatments, and to several different teeth. All the payments due in respect of the components within a claim are added together, and summarised in a single payment record for that course of treatment. These payment records are in turn recorded and summarised on a monthly payment schedule for reporting to the individual dentist.

For each course of treatment undergone by each patient in the longitudinal dataset, there is thus a record of the last date of attendance. It is also known on which payment schedule each course of treatment appeared – generally the month immediately after the month of treatment. By grouping the claims for courses of treatment by patient, and ordering by last date of attendance, it is possible to establish, for each course, the interval to the next payment schedule in which the patient had a subsequent course of treatment, and if there was no subsequent course, the interval till the last payment schedule (March 2002) included in the study.

The next step is to form frequency tables for the intervals between treatment and next payment schedule, and then cumulative frequencies of periods of claims remaining after a specified time interval, subdivided between those with a subsequent attendance and those without.

Let M be the maximum number of months of observation following the attendance of a patient. In the case of this study, M=134 months (January 1991 is month 0). For practical purposes, it is assumed that a patient who has not re-attended after M months may be regarded as having left the population permanently.

Let R_i be the observed number of patients who re-attended after i months, and N_i the number who were tracked for a total of i months but did not re-attend (i=1,…,M).

The probability that a patient observed without re-attendance for i months would eventually re-attend was estimated as

$$P(i) = \frac{\sum_{j=i+1}^{M} R_i}{\sum_{j=i+1}^{M} (N_j + R_j)}$$

Each point estimate of probability of return is based on a sample of n claims remaining, ranging from $\sum_{i=1}^{M}(R_i + N_i)$, the total over all courses for an interval of less than one month, to N_M, the number remaining from the first month, for an interval of 134 months. By standard binomial sampling theory the corresponding standard error can be estimated by $\sqrt{(pq/n)}$, where p is the estimated probability of return and q=1-p. This result could be used to construct a confidence interval around each of the estimates in the final column of the frequency table.

3.4.2 Incorporation into Kaplan-Meier Methodology

The methodology described below assumes a homogeneous patient population with a common G(m) re-attendance probability function. In practice this method was used on each of eight patient age groups, and the results then combined.

Armed with the empirical function G(m), the probability that a patient will return after a gap without re-attendance of m months from last visit to last payment schedule processed, the Kaplan-Meier analysis can be modified to take follow-up time into account. The theory is straight-forward – replace the count of censored cases at any time period by the expected number, a count derived by multiplying each censored case by (1-G(m)), where m is the number of months between the last time that patient attended and March 2002. Note that at this stage it has not yet been decided what time should be chosen for the effective time of censoring – this is covered in section 3.4.3. However, the choice of censor time is irrelevant to the method of adjusting the Kaplan-Meier method, since it is the follow-up time for the patient's last course, not that for the course with the restoration, which needs to be used.

In practice, however, there are some hurdles to overcome if this adjustment is to be made efficiently. Writing a new suite of programs with a modified Kaplan-Meier routine is possible, but very time consuming, and lacks the support of a commercial statistical software company such as SPSS. Within a package such as SPSS, there are at least two ways in which the existing Kaplan-Meier program can be used to produce adjusted figures.

One method involves applying a uniform random allocation function to cases which have not re-attended. This would have probability G(m) of censoring at the end of the observation period (31/12/01) and 1-G(m) of censoring before then (at the time determined in the next section). This method has been used to estimate the standard errors of the survivor function percentiles, for comparison with direct calculation and the SPSS estimates of the unadjusted survivor function percentiles.

The other method, which has been adopted for the estimation of the survivor function and its percentiles, is to re-weight such cases, in proportion to G(m). This has the advantage that it is repeatable and free from the chance of extreme distortion. Unfortunately, the weighting process in SPSS is limited to integer weights, and there is a practical machine limit of a maximum weight of 1000. This nevertheless provides a reasonable level of precision, given that the estimates of G(m) are themselves subject to some variation (as described in 3.4.1). Cases where the patient did re-attend were therefore given a weight of

1000, and the others were split into two cases, one with weight 1000G(m) and one with weight 1000(1-G(m)). The other complication with integer weights is that the apparent underlying sample size is inflated, so that the calculations of significance tests and confidence intervals are incorrect. This is discussed in a later section (3.4.4).

3.4.3 Time of Censoring

To give a feel for the impact of the choice of censoring date, four options were compared (section 4.3.2): date of last dental attendance, end of observation period (31st December 2001), half-way between these two dates, and one year after the date of last attendance. In view of the results, the assumed censoring date was taken to be 365 days after the last visit.

3.4.4 Confidence Intervals

Finally, this section considers the confidence intervals and significance levels appropriate to adjusted Kaplan-Meier empirical survival functions. Each point at which the cumulative survival probability is calculated is formed from a ratio of two random variables: the number of re-interventions occurring after exactly that time interval and the number of restored teeth at risk at the time of re-intervention. The effect of the adjustment is to reduce the number of censored cases, and replace them with uncensored ones. This results in an increase in the effective sample size. However, the standard error also depends on the value of the survivor function estimate and the slope of the survivor function. Provided the adjustment function does not itself introduce more variability than the increase in sample size removes, then the standard errors and significance tests carried out with unadjusted data should be conservative when compared with those for adjusted data. This section provides the methodology for exploring whether this is in fact the case, and for justifying the choice made in section 3.4.2 of the method used for estimating the standard error of the percentiles of the survivor function and associated statistics.

As an example, consider the standard error of the median – the time by which half of all the restorations originally placed can be expected to have received a re-intervention. Standard theory (Collett, 1994) estimates this by the formula

$$\text{s.e.}\{\hat{t}(50)\} = \frac{1}{\hat{f}\{\hat{t}(50)\}}\ \text{s.e.}[\hat{S}\{\hat{t}(50)\}],$$

where $\hat{f}\{\hat{t}(50)\}$ is the estimated slope, with the sign reversed, of the survivor function at the 50th percentile, approximated in SPSS algorithms by taking a line through the 55th and 45th percentiles, or the nearest points outside them. Given the density of the DPB data, a shorter interval could equally well be used, and in the direct calculation of the standard error of the 95th percentile the 91st and 99th percentiles have been used here. The SPSS software is constrained to use five percentile points, and is therefore unable to calculate the standard error for the 95th and higher percentiles.

The standard error of the estimated cumulative survival at the median, the 50th percentile, s.e.[$\hat{S}\{\hat{t}(50)\}$], can be estimated from Greenwood's formula,

$$\text{s.e. }\{\hat{S}(t)\} \approx [\hat{S}(t)]\{\sum_{j=1}^{k} \frac{d_j}{n_j(n_j - d_j)}\}^{\frac{1}{2}},$$

where n_j and d_j are, respectively, the number of surviving restorations and restorations retreated at time t(j), and k is such that t(k)<= t <= t(k+1). In this case $n_j = n_{j-1} - d_{j-1} - \sum_{m=1}^{135} c_{m,j-1}$(1-G(m)) , where $c_{m,j}$ is the number of cases not seen again after time j and followed up for m months – 135 is the maximum possible value for m, given a study with first observation month January 1991 and last observation month March 2002.

3.4.5 Empirical Analyses

The methods described in sections 3.4.1 to 3.4.4 were then used in conjunction with standard Kaplan-Meier analysis using SPSS to develop a series of univariate Kaplan-Meier charts. Log cumulative hazard plots were used for those cases where categorical variables suggested substantial (as well as statistically significant) relationships between the variables and the scale of the survival curve to establish whether a proportional hazards assumption was consistent with the observed survival pattern. The univariate analyses were supplemented by multivariate charts, subdividing the population according to combinations of variables.

Charts were also created to show how the characteristics of the re-intervention course of treatment varied with time.

3.5 Methodology for Modelling

In the light of the initial empirical findings, several models and simulations were created to illustrate how the observed data could reflect underlying factors.

3.5.1 The Kink at Six Months

The early life analyses (section 4.1.5) contain a particularly interesting feature, an inflexion at around 180 days (six months) after the placing of the restoration. One possible explanation for such a feature could be an increased hazard (that is, likelihood of re-intervention), at the time of the next routine attendance. Accordingly, a simulation model was set up to show how a mixture of two distributions, an exponential and an interval-censored exponential, could produce such a pattern.

Two runs of this simulation were carried out, using programs written with SPSS syntax. The first assumed a fixed interval (of six months) for the censoring interval. The second simulation allowed the interval itself to vary according to an exponential distribution.

3.5.2 The Effect of Ignoring Variation in the Historical Rate of Placing Fillings

This simulation was prompted by concern about the effect of assuming constant historical provision rates on estimates based on cross-sectional data – generally using the first of the three cross-sectional methods described earlier in this chapter.

The simulation was based on a linear survivor function and was created using an Excel spreadsheet.

3.5.3 The Effect of Ignoring Restorations which Received Re-interventions Other than Replacement

Another feature of the existing literature was the suggestion that the distribution of the ages of restorations replaced by other restorations was a satisfactory estimate of the points of the survivor function.

This simulation used a linear underlying survivor function but assumed that unobserved ‘termination’ cases, such as crowns and extractions, occurred proportionately more often in early years, with consequent distortion of the observed distribution of age at replacement. This simulation was again created on an Excel spreadsheet.

3.5.4 Cox Regression Semi-parametric Model

In the light of the empirical findings about significant factors and the extent to which their hazards appeared to be proportional, a series of Cox-Regression models was created using SPSS standard statistical software, applied to the data on which the Kaplan-Meier analyses were based. The random censoring method was used to allow for the probability of re-attendance, in order to produce realistic significance levels.

The Cox Regression model assumes that the hazard function h(t) is given by $h_i(t)=\psi(\mathbf{x}_i)\,h_0(t)$, where ψ is some function of the set of covariate values $\mathbf{x}_i$ of the ith individual in the sample and $h_0(t)$ is the baseline hazard function (where $\mathbf{x}_i = \mathbf{0}$ and $\psi(\mathbf{0}) = 1$). Since ψ cannot be negative, $\psi(\mathbf{x}_i)$ can be written as $\exp(\eta_i)$, where $\eta_i = \sum_{j=1}^{p} B_j x_{ji}$, assuming a linear regression on x_{ji}, with coefficients B_j.

The value of $\mathrm{Exp}(B_j)$ is then the constant of proportionality for covariate x_j.

Furthermore, this model assumes that there is no interaction between the covariates, though there may be confounding.

Forward step-wise Cox-Regression analysis was applied to a particular subset of the data. This subset consisted of restorations placed before 2000 in patients with a total of at least four attendances, of which at least one was in the last two years of the observation period. The likelihood ratio statistic was used as the inclusion criterion, with significance level 0.05 for inclusion of a new variable in the model. Tunnel restorations and root fillings without direct fillings were excluded from the subset, since their hazard functions were clearly not proportional to those of other types of direct restoration. The Cox-Regression analysis included backward testing that all the included covariates remained significant (with significance level 0.10) using the likelihood-ratio statistic based on the maximum partial likelihood estimates. The variables used as covariates included a wide range of additional indicators (categorical variables with values 0 and 1), such as the presence of other treatments on the same tooth or in the same course of treatment as that in which the restoration was placed. Where covariates consisted of categorical variables they were replaced by a set of n-1 contrast variables, where n is the number of values taken by the original categorical variable. The only covariate variables treated as continuous were patient age (in years), mean annual scale fees (in pence), median interval between attendances (in days), and year of placement (in years). In effect, the model fits only the linear component of these variables.

As part of the output from this process, plots were obtained of underlying base hazard functions and estimates made of the constants of proportionality, and hence of the increased or reduced risk associated with each level of each factor.

3.5.5 Underlying Survivor Functions

The base hazard function derived from the Cox Regression model was then subjected to curve fitting analyses, including standard multiple regression for polynomial functions and non-linear estimation of Weibull functions, using the SPSS non-linear regression procedure.

3.6 Methodology for Replication

Finally, all the data assembly and empirical analysis programs for the full longitudinal analysis were re-run on a second sub-sample (sub-sample 3), to confirm the robustness of the patterns and relationships inferred from the main analysis of the full longitudinal dataset.

4 RESULTS

The results displayed within this section form only an extract of the more extensive work which can be seen in the appendix, which contains SPSS program and output files detailing both the creation of the datasets and their subsequent comprehensive analyses, including a large number of Kaplan-Meier plots, together with log rank tests of the significance of differences between the survivor functions for different subgroups. When comparing this work with other sources it is as well to remember that each point on each survival plot represents a day on which at least one restoration of the appropriate type has received re-intervention. The density of the points on the charts gives a useful visual reminder of the massive body of data on which the results are based.

4.1 Early Life of Restorations

This is a study of re-intervention, rather than of failure or replacement. The re-intervention on the previously restored tooth may not be directly associated with the original restoration. The interval to first re-intervention, and the type of first re-intervention, cover a wider range of circumstances, but, particularly during the first year after the placement of the restoration, include occasions involving failure or replacement of the restoration as component events.

4.1.1 Characteristics of the Sample Population for Patients Born in 1965

Table 4.1 Patient sex * Number of teeth filled

		Patient Sex		Total
		Female	Male	
Number of Teeth Filled	1	5,982	4,112	**10,094**
	2	2,101	1,619	**3,720**
	3	812	718	**1,530**
	4	396	345	**741**
	5	176	200	**376**
	6	106	112	**218**
	7	76	85	**161**
	8	28	48	**76**
	9	29	33	**62**
	10	12	19	**31**
	11	5	15	**20**
	12	3	6	**9**
	13	5	9	**14**
	14		3	**3**
	15	1	2	**3**
	16	2	2	**4**
Total		**9,734**	**7,328**	**17,062**

Data for a total of 17,062 patients for whom claims for directly placed restorations were included in payment schedules in March 2000 are included in this analysis. All the patients were born in 1965, so their age at date of treatment was around 35 years. As Table 4.1 indicates, there were more women than men, but the men had proportionately more courses of treatment containing multiple restorations.

Table 4.2 Number of teeth filled, by tooth position, mouth quadrant and sex of patient

Patient Sex			Quadrant LL	LR	UL	UR	Total
Female	Tooth Position	1	114	109	508	504	**1,235**
		2	86	65	418	413	**982**
		3	112	127	361	359	**959**
		4	341	321	518	610	**1,790**
		5	569	587	651	697	**2,504**
		6	1,246	1,159	1,224	1,189	**4,818**
		7	940	945	986	804	**3,675**
		8	305	282	261	249	**1,097**
		Total	**3,713**	**3,595**	**4,927**	**4,825**	**17,060**
Male	Tooth Position	1	62	79	429	409	**979**
		2	70	74	415	379	**938**
		3	106	116	373	328	**923**
		4	282	268	461	474	**1,485**
		5	454	451	532	541	**1,978**
		6	1,019	997	954	952	**3,922**
		7	836	831	773	713	**3,153**
		8	320	258	242	282	**1,102**
		Total	**3,149**	**3,074**	**4,179**	**4,078**	**14,480**

When this is translated into the total number of teeth restored, 17,060 were for female patients and 14,480 for male patients. The pattern of restoration across the tooth positions and quadrants of the mouth was similar for males and females, with the largest number of restorations on the first molars (tooth position 6), followed by second molars and second premolars (Table 4.2).

For the first five anterior tooth positions, to the second premolars, there were substantially more direct restorations in the maxillary arch than in the lower jaw. This was particularly marked for the incisors, for which there were more than five times as many upper teeth restored as lower.

The following tables (Table 4.3 to Table 4.10) summarise, by tooth position, the distribution of the different types of filling provided. The tables refer to GDS treatment codes as follows:

1401 Single surface amalgam

1402 Two surface amalgam, not MO or DO

1403 MO or DO amalgam

1404 MOD amalgam

1421 Composite Resin

1426 Glass Ionomer

These tables include 117 cases where the same tooth was restored twice, on two different dates, in the March 2000 schedules. Hence the table totals are slightly greater than those in the previous tables.

Table 4.3 Tooth Position 1 Tooth Summary Count

		Tooth Position 1						
		Treatment Code						**Tooth Summary**
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	4	1			159	14	**178**
	LR	2				168	20	**190**
	UL	13	1			866	67	**947**
	UR	14				834	69	**917**
Tooth Summary		**33**	**2**			**2,027**	**170**	**2,232**

The pattern of restoration types provided is consistent with the restrictions in the Statement of Dental Remuneration which governs the circumstances in which different types of restoration materials may be used in the General Dental Services. In particular, tooth-coloured materials such as composite resin and glass ionomer may not be used on occlusal surfaces on posterior teeth.

Table 4.4 Tooth Position 2 Tooth Summary Count

		Tooth Position 2						
		Treatment Code						**Tooth Summary**
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	1				142	13	**156**
	LR					129	10	**139**
	UL	10				747	79	**836**
	UR	5				708	85	**798**
Tooth Summary		**16**				**1,726**	**187**	**1,929**

Table 4.5 Tooth Position 3 Tooth Summary Count

		Tooth Position 3						
		Treatment Code						**Tooth Summary**
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	1				167	50	**218**
	LR	5	1			174	64	**244**
	UL	14				622	102	**738**
	UR	13	2			578	96	**689**
Tooth Summary		**33**	**3**			**1,541**	**312**	**1,889**

On the incisors and canines, most restorations involved the use of resin composites, followed by glass ionomer, with just a few amalgams, mostly item 1401 (single surface).

Table 4.6 Tooth Position 4 Tooth Summary Count

		Tooth Position 4						
		Treatment Code						**Tooth Summary**
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	43	1	191	31	222	136	**624**
	LR	40	5	171	35	209	131	**591**
	UL	63	4	433	175	194	111	**980**
	UR	62	6	491	177	213	138	**1,087**
Tooth Summary		**208**	**16**	**1,286**	**418**	**838**	**516**	**3,282**

Table 4.7 Tooth Position 5 Tooth Summary Count

Tooth Position 5

		Treatment Code						
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	**Tooth Summary**
Quadrant	**LL**	89	9	533	133	143	120	**1,027**
	LR	86	11	560	114	146	122	**1,039**
	UL	84	9	586	323	101	82	**1,185**
	UR	86	6	591	349	121	91	**1,244**
Tooth Summary		**345**	**35**	**2,270**	**919**	**511**	**415**	**4,495**

Table 4.8 Tooth Position 6 Tooth Summary Count

Tooth Position 6

		Treatment Code						
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	**Tooth Summary**
Quadrant	**LL**	357	124	991	415	164	226	**2,277**
	LR	349	103	893	447	164	212	**2,168**
	UL	319	116	1,012	446	135	159	**2,187**
	UR	302	105	982	408	174	178	**2,149**
Tooth Summary		**1,327**	**448**	**3,878**	**1,716**	**637**	**775**	**8,781**

Table 4.9 Tooth Position 7 Tooth Summary Count

Tooth Position 7

		Treatment Code						
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	**Tooth Summary**
Quadrant	**LL**	514	99	744	178	90	158	**1,783**
	LR	494	81	785	173	104	144	**1,781**
	UL	424	91	845	232	67	103	**1,762**
	UR	408	79	705	202	41	88	**1,523**
Tooth Summary		**1,840**	**350**	**3,079**	**785**	**302**	**493**	**6,849**

Table 4.10 Tooth Position 8 Tooth Summary Count

		Tooth Position 8						
		Treatment Code						**Tooth Summary**
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	319	49	161	27	29	40	**625**
	LR	275	35	157	23	18	33	**541**
	UL	217	28	191	16	15	36	**503**
	UR	226	28	199	26	19	33	**531**
Tooth Summary		**1,037**	**140**	**708**	**92**	**81**	**142**	**2,200**

For posterior teeth there was a full range of restoration types, at least within the definition specified in the SDR. It should be remembered that composite resin and glass ionomer restorations for such teeth must all be in class V cavities, on the buccal or lingual surfaces, while single surface amalgams may also be on the occlusal surfaces of teeth.

These six types of restoration can be further subdivided by examination of the accompanying additional treatment codes – GDS codes 1422 to 1425 and code 1431. The codes are defined as follows:

For incisors, the presence of one or more of codes 1422 to 1424 is indicative of restorations of Classes III and IV – since these codes indicate whether the incisal angles or edge are involved. Item 1422 involves one incisal angle, 1423 the incisal edge not involving an incisal angle, and 1424 both incisal angles. Item 1425 relates to restoration of a cusp tip of a premolar or a buccal cusp tip of a first molar tooth. For all teeth item 1431 indicates the use of a dentine pin or pins. There were also some occasions when two different types of filling were placed on the same tooth in the same course of treatment. In these cases the filling with the lowest SDR code (the simplest amalgam, then progressively more complex amalgam, followed by composite resin, followed by glass ionomer) was recorded as the main filling treatment. Table 4.11 indicates the relative frequency of different combinations of additional filling treatment items in the March 2000 directly placed restoration claims.

Table 4.11 The variety of additional filling treatments prescribed on the same tooth

		Frequency	Percent
Combination of additional treatment items	./ ./ .	28,244	89.2
	1402/ ./ .	5	.0
	1402/1431/ .	1	.0
	1403/ ./ .	28	.1
	1403/1431/ .	2	.0
	1404/ ./ .	8	.0
	1404/1431/ .	11	.0
	1421/ ./ .	184	.6
	1421/1425/ .	2	.0
	1421/1431/ .	8	.0
	1422/ ./ .	747	2.4
	1422/1423/ .	30	.1
	1422/1423/1424	1	.0
	1422/1424/ .	2	.0
	1422/1426/ .	3	.0
	1422/1431/ .	66	.2
	1423/ ./ .	208	.7
	1423/1424/ .	4	.0
	1423/1431/ .	4	.0
	1424/ ./ .	80	.3
	1424/1431/ .	3	.0
	1425/ ./ .	109	.3
	1425/1426/ .	1	.0
	1425/1431/ .	32	.1
	1426/ ./ .	155	.5
	1426/1431/ .	11	.0
	1431/ ./ .	1,708	5.4
	Total	31,657	100.0

Nearly ninety per cent of the restored teeth had no additional treatment items. The most common additional item was 1431, indicating a pinned restoration, followed by 1422 and 1423, indicating class IV cavities. After that come about one per cent of restored teeth with two fillings on the same tooth – generally composite resin or glass ionomer combined with amalgam. Only a tiny proportion of restorations had more than one additional treatment.

A natural grouping of these additional treatments can be summarised as in the following table.

Table 4.12 Additional Treatments (summarised)

Additional Treatments (summarised)

		Frequency	Percent
Combination of additional treatment items	**None**	28,244	89.2
	Other filling	419	1.3
	One incisal angle	846	2.7
	Incisal edge	216	.7
	Two incisal angles	83	.3
	Dentine pin	1,740	5.5
	Cusp tip restored	109	.3
	Total	31,657	100.0

4.1.2 Overall Re-intervention Rates

This section considers, by tooth position, the proportion of teeth experiencing re-intervention within 365 days (measured from date of placement of the March 2000 course of treatment to the date of acceptance of the first subsequent course of treatment involving the same tooth). This is presented for each tooth in the form of a table for each tooth position, giving a cross-break between quadrant and first treatment type (GDS item code). A further breakdown by patient sex can be seen in the appendix. The pattern within male and female patients was similar, except that female patients had a generally higher re-intervention rate than males.

In interpreting these tables, heed must be taken of the sample sizes (given in the section 4.1.1 above) underlying the percentages quoted. Those percentages based on fewer than 100 cases are printed in italics. The number of re-interventions for each cell in the tables can be found within the detailed tables in the appendix.

Table 4.13 Tooth position 1 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	*0%*	*.0%*	.	.	10.7%	*.0%*	9.6%
	LR	*.0%*	*.*	.	.	8.3%	*5.0%*	7.9%
	UL	*15.4%*	*.0%*	.	.	11.0%	*13.4%*	11.2%
	UR	*7.1%*	*.*	.	.	12.6%	*7.2%*	12.1%
Tooth Summary		*9.1%*	*.0%*	.	.	11.4%	8.8%	11.2%

Table 4.14 Tooth position 2 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	**1402**	**1403**	**1404**	**1421**	**1426**	
Quadrant	**LL**	*.0%*	.	.	.	11.3%	*7.7%*	10.9%
	LR	*.*	.	.	.	9.3%	*30.0%*	10.8%
	UL	*10.0%*	.	.	.	9.5%	*8.9%*	9.4%
	UR	*.0%*	.	.	.	11.7%	*9.4%*	11.4%
Tooth Summary		*6.3%*	.	.	.	10.5%	10.2%	10.5%

For incisors the only treatment item with sufficiently high incidence to merit inference was item 1421 (composite resin). There was a higher re-intervention rate, for composite resin restorations, on upper right and lower left incisors. Overall the re-intervention rate was around ten or eleven per cent.

Table 4.15 Tooth position 3 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	*.0%*	.	.	.	10.2%	*6.0%*	9.2%
	LR	*.0%*	*.0%*	.	.	7.5%	*3.1%*	6.1%
	UL	*21.4%*	.	.	.	9.2%	2.9%	8.5%
	UR	*7.7%*	*.0%*	.	.	9.3%	*7.3%*	9.0%
Tooth Summary		*12.1%*	*.0%*	.	.	9.1%	4.8%	8.5%

For canines item 1421 again dominated. Glass ionomer (1426) appeared, overall, to experience a lower re-intervention rate on canine teeth. The overall one-year re-intervention rate for canines was around eight or nine per cent.

Table 4.16 Tooth position 4 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	*7.0%*	*.0%*	7.9%	*6.5%*	8.6%	2.9%	6.9%
	LR	*5.0%*	*.0%*	10.5%	*14.3%*	10.5%	8.4%	9.8%
	UL	*9.5%*	*25.0%*	6.2%	13.1%	8.8%	9.0%	8.6%
	UR	*6.5%*	*16.7%*	5.1%	7.9%	6.6%	11.6%	6.8%
Tooth Summary		7.2%	*12.5%*	6.6%	10.5%	8.6%	7.9%	7.9%

Table 4.17 Tooth position 5 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	*7.9%*	*22.2%*	10.1%	10.5%	12.6%	5.8%	9.9%
	LR	*4.7%*	*18.2%*	8.0%	12.3%	8.9%	12.3%	9.0%
	UL	*9.5%*	*.0%*	6.7%	8.4%	9.9%	*15.9%*	8.2%
	UR	*7.0%*	*16.7%*	7.1%	8.9%	14.9%	*16.5%*	9.1%
Tooth Summary		7.2%	*14.3%*	7.9%	9.4%	11.5%	12.0%	9.0%

For premolars all treatment types except 1402 (occluso-lingual and occluso-buccal) were sufficiently well represented to give meaningful re-intervention rates. For first premolars no particular relationships between the variables stood out, and the overall re-intervention rate was around eight per cent. For second premolars the overall re-intervention rate was around nine per cent.

Table 4.18 Tooth position 6 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	9.2%	9.7%	12.4%	13.3%	14.0%	19.5%	12.7%
	LR	5.7%	3.9%	10.4%	12.3%	14.6%	17.9%	10.8%
	UL	5.3%	11.2%	12.1%	10.5%	14.8%	16.4%	11.2%
	UR	6.3%	7.6%	9.1%	12.0%	11.5%	19.7%	10.2%
Tooth Summary		6.7%	8.3%	11.0%	12.0%	13.7%	18.5%	11.3%

For first molars, the number of cases was sufficiently large and the spread sufficiently wide for inference to be drawn from all the cells in the tables. There was a significant difference ($p<0.05$) between different treatments, with a range extending from under seven per cent for single surface amalgams to over eighteen per cent for glass ionomers. Overall, the re-intervention rate was around eleven per cent.

Table 4.19 Tooth position 7 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	5.3%	*10.1%*	8.7%	14.6%	*12.2%*	18.4%	9.4%
	LR	4.3%	*4.9%*	11.7%	9.2%	9.6%	20.1%	9.7%
	UL	3.8%	*8.8%*	8.9%	13.4%	*17.9%*	15.5%	9.0%
	UR	2.2%	*3.8%*	9.1%	8.9%	*7.3%*	*15.9%*	7.3%
Tooth Summary		4.0%	7.1%	9.6%	11.6%	11.9%	17.8%	8.9%

Second molars presented a similar picture. There was again a clear hierarchy of treatment types, ranging in this case from around four per cent for single surface amalgams to eighteen per cent for glass ionomer.

Table 4.20 Tooth position 8 rate of re-intervention within one year

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Quadrant	LL	2.2%	*10.2%*	6.2%	*11.1%*	*6.9%*	*7.5%*	4.8%
	LR	2.5%	*8.6%*	7.0%	*4.3%*	*11.1%*	*12.1%*	5.2%
	UL	4.1%	*10.7%*	10.5%	*31.3%*	*13.3%*	*8.3%*	8.3%
	UR	4.4%	*7.1%*	4.5%	*19.2%*	*.0%*	*12.1%*	5.6%
Tooth Summary		3.2%	9.3%	7.1%	*15.2%*	*7.4%*	9.9%	5.9%

Only items 1401 and 1403 had sufficient numbers on third molars for reliable inference. Restricted to these treatments, there were clearly around twice as many re-interventions, relatively, for 1403 (MO or DO) compared with 1401 (single surface). Overall, around six per cent of third molars had re-interventions within a year.

4.1.3 Re-intervention Rates for Particular Subgroups

Other factors included in these analyses comprise the patient's sex and exemption status, other treatment items concurrent with the main treatment, and whether the dentist who provided the re-intervention was the same as the one who provided the original treatment.

Patient sex was clearly a factor. For most sub-populations, the rate of re-intervention within one year was around two percentage points higher for females than for males. This has already been noted in comments on tables of overall rate of re-intervention. Table 4.21 summarises the differences across the different types of filling.

Table 4.21 Summary re-intervention rates by patient sex

Summary re-intervention rates by Patient Sex

		Treatment Code						Tooth Summary
		1401	1402	1403	1404	1421	1426	
Patient Sex	Male	3.8%	6.8%	8.9%	10.3%	9.5%	11.2%	8.5%
	Female	6.1%	9.5%	9.5%	11.9%	11.6%	14.0%	10.3%
All Teeth Summary		5.0%	8.2%	9.3%	11.2%	10.6%	12.8%	9.5%

The following tables show the relationship between exemption from or remission of patient charges and the rate of re-intervention, by patient sex and type of restoration. It can be seen that for all six types of restoration, and for both male and female patients a higher proportion received re-intervention within one year if the patient did not have to pay for the original restoration. The difference varied between types, reaching a maximum of about two percentage points for composite resin and glass ionomer.

Table 4.22 Re-intervention rates by treatment type and patient charge status – male patients

Re-intervention rates by treatment type and patient charge status – Male patients

		Treatment Code						All Teeth Summary	
		1401	1402	1403	1404	1421	1426	rate	base (n)
Patient Status	Exempt/Remitted	4.2%	5.1%	9.3%	11.6%	10.5%	10.7%	9.2%	4,550
	Full Charge	3.7%	7.4%	8.7%	9.9%	8.8%	11.6%	8.2%	9,980
All Teeth Summary		3.8%	6.8%	8.9%	10.3%	9.5%	11.2%	8.5%	14,530

Table 4.23 Re-intervention rates by treatment type and patient charge status – female patients

Re-intervention rates by treatment type and patient charge status – Female patients

		Treatment Code						All Teeth Summary	
		1401	1402	1403	1404	1421	1426	rate	base (n)
Patient Status	Exempt/Remitted	5.8%	10.7%	9.8%	12.3%	12.4%	15.5%	10.9%	9,077
	Full Charge	6.5%	8.5%	9.3%	11.5%	10.5%	11.8%	9.6%	8,050
All Teeth Summary		6.1%	9.5%	9.5%	11.9%	11.6%	14.0%	10.3%	17,127

In this age group there were proportionately more exempt female patients than males – principally because of the exemptions for pregnant and nursing mothers. Because females had a higher overall re-intervention rate than males, the differential across the whole population was greater than that for either males or females separately.

Table 4.24 Re-intervention rates by treatment type and patient charge status – all patients

Re-intervention rates by treatment type and patient charge status – all patients

		Treatment Code						All Teeth Summary	
		1401	1402	1403	1404	1421	1426	rate	base (n)
Patient Status	**Exempt/Remitted**	5.2%	8.9%	9.6%	12.1%	11.7%	13.8%	10.4%	13,627
	Full Charge	4.9%	7.9%	9.0%	10.6%	9.6%	11.7%	8.8%	18,030
All Teeth Summary		5.0%	8.2%	9.3%	11.2%	10.6%	12.8%	9.5%	31,657

Table 4.25 Re-intervention rate by type of additional treatment

		Treatment Code						All Teeth Summary	
		1401	1402	1403	1404	1421	1426	Re-intervention rate	Base number for rate (n)
Additional Treatment	**None**	4.8%	8.5%	8.9%	11.0%	9.7%	12.7%	9.0%	28,244
	Other filling	12.2%	*8.3%*	10.0%	*14.1%*	*22.2%*	.	12.2%	419
	One incisal angle	.	.	.	.	14.2%	.	14.2%	846
	Incisal edge	.	.	.	.	15.3%	.	15.3%	216
	Two incisal angles	.	.	.	.	*18.1%*	*.*	*18.1%*	83
	Dentine pin	.	*2.6%*	13.5%	12.1%	*14.3%*	*31.8%*	12.9%	1,740
	Cusp tip restored	.	.	.	.	17.4%	.	17.4%	109
All Teeth Summary		5.0%	8.2%	9.3%	11.2%	10.6%	12.8%	9.5%	31,657

Additional treatments, such as dentine pins and, in the case of incisors, additional fees for incisal angles and incisal edges (class IV as opposed to class III), were generally associated with a higher rate of re-intervention.

Table 4.26 Was re-intervention by same dentist?

		Treatment Code						Overall
		1401	1402	1403	1404	1421	1426	
Dentist who re-intervened	**different**	15.6%	*25.6%*	23.6%	18.1%	19.0%	21.3%	**20.7%**
	same	84.4%	*74.4%*	76.4%	81.9%	81.0%	78.7%	**79.3%**
Total (=100%)		243	82	1,038	441	814	385	3,003

Since this exercise did not consider other treatments than those on specific teeth, it is not possible, absolutely, to determine whether more patients with re-intervention within one year were retreated by different dentists than would have been otherwise expected. However, the table shows that around one in five of the re-interventions within one year was performed by a dentist different from the dentist who provided the original restoration.

4.1.4 Re-intervention Type

Although this is a study of re-intervention, rather than of failure or replacement, it is of interest to know what the first replacement treatment was for any particular initial treatment. Detailed tables are available within the appendices, but the following tables summarize the position. In reading the tables, heed should be paid to the size of the sample which forms the percentage base (‘Total number (=100%)’). Where this is below 100, the percentages cannot confidently be quoted to within ten percentage points. Those percentages based on fewer than 100 cases are printed in italics.

Table 4.27 Re-intervention type: tooth position 1

	Original Treatment Code	**1401**	**1402**	**1403**	**1404**	**1421**	**1426**	**Overall**
	1401 Amalgam one surface	*33.3%*				1.3%		**1.6%**
	1421 Resin Composite	*33.3%*				74.0%	*26.7%*	**70.7%**
	1426 Glass Ionomer					2.6%	*13.3%*	**3.2%**
Type of Re-intervention	**Crowns/Inlays**					10.8%	*40.0%*	**12.4%**
	Extractions					3.0%	*6.7%*	**3.2%**
	Stoning					4.3%	*6.7%*	**4.4%**
	Other	*33.3%*				3.9%	*6.7%*	**4.4%**
Total number (= 100%)		3				231	15	249

Table 4.28 Re-intervention type: tooth position 2

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	1401 Amalgam one surface					0.5%		**0.5%**
	1402 Amalgam two surface					0.5%		**0.5%**
	1421 Resin Composite					66.5%	*26.3%*	**62.4%**
	1426 Glass Ionomer					3.8%	*36.8%*	**6.9%**
	Crowns/Inlays	*100.0%*				13.7%	*21.1%*	**14.9%**
	Extractions					1.1%	*5.3%*	**1.5%**
	Stoning					3.8%		**3.5%**
	Other					9.9%	*10.5%*	**9.9%**
Total number (= 100%)		1				182	19	202

Table 4.29 Re-intervention type: tooth position 3

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	1401 Amalgam one surface	*25.0%*				.7%	*6.7%*	**1.9%**
	1402 Amalgam two surface					1.4%		**1.3%**
	1421 Resin Composite	*50.0%*				70.9%	*40.0%*	**67.5%**
	1426 Glass Ionomer					9.2%	*46.7%*	**12.5%**
	Crowns/Inlays					9.9%	*6.7%*	**9.4%**
	Extractions	*25.0%*				2.1%		**2.5%**
	Stoning					1.4%		**1.3%**
	Other					4.3%		**3.8%**
Total number (= 100%)		4				141	15	160

For incisors and canines, most direct restorations were composite resin, and two thirds of those composite resin treated teeth that had re-interventions within one year were retreated with the same material. The remainder were mostly glass ionomer, and they had a wider range of re-interventions if they were retreated within one year. Although glass ionomer was the most common re-intervention for glass ionomer fillings, it was closely followed by composite resin.

Table 4.30 Re-intervention type: tooth position 4

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	1401 Amalgam one surface	*20.0%*		*5.9%*	*6.8%*	*2.8%*	*2.4%*	**5.4%**
	1403 Amalgam MO or DO	*26.7%*		*35.3%*	*13.6%*	*11.1%*	*22.0%*	**22.0%**

	1404 Amalgam MOD	6.7%	100.0%	10.6%	27.3%	2.8%		10.0%
	1421 Resin Composite	20.0%		15.3%	9.1%	55.6%	12.2%	25.1%
	1426 Glass Ionomer			5.9%	6.8%	11.1%	34.1%	11.6%
	Crowns/Inlays	20.0%		15.3%	20.5%	9.7%	17.1%	15.1%
	Extractions			7.1%	6.8%	1.4%	2.4%	4.2%
	Stoning			2.4%	2.3%	4.2%	2.4%	2.7%
	Other	6.7%		2.4%	6.8%	1.4%	7.3%	3.9%
Total number (= 100%)		15	2	85	44	72	41	259

Table 4.31 Re-intervention type: tooth position 5

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	1401 Amalgam one surface	28.0%		3.9%	4.7%	3.4%	4.0%	5.4%
	1402 Amalgam two surface			1.1%	2.3%		4.0%	1.5%
	1403 Amalgam MO or DO	12.0%		45.6%	7.0%	10.2%	10.0%	25.2%
	1404 Amalgam MOD	4.0%	20.0%	11.1%	26.7%	5.1%	6.0%	12.6%
	1421 Resin Composite			2.2%	7.0%	33.9%	8.0%	8.4%
	1426 Glass Ionomer		40.0%	4.4%	5.8%	11.9%	32.0%	9.4%
	Crowns/Inlays	32.0%	20.0%	12.2%	20.9%	20.3%	14.0%	16.8%
	Extractions	16.0%	20.0%	6.1%	8.1%	1.7%	6.0%	6.7%
	Stoning	4.0%		6.7%	7.0%	6.8%	4.0%	6.2%
	Other	4.0%		6.7%	10.5%	6.8%	12.0%	7.9%
Total number (= 100%)		25	5	180	86	59	50	405

For premolars there was a wider range of re-interventions, with substantial numbers of item 1403 and 1404 (MO or DO, or MOD) amalgam fillings. Although re-intervention of the same type was the most common, a substantial number of alternative fates were experienced. In particular, around 15% of the restorations on premolars with re-intervention within one year were replaced by crowns, and around 5% were extracted.

Table 4.32 Re-intervention type: tooth position 6

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	1401 Amalgam one surface	20.2%	8.1%	6.1%	4.4%	4.6%	6.3%	7.0%
	1402 Amalgam two surface	2.2%	29.7%	2.1%	2.9%	1.1%	2.1%	3.2%
	1403 Amalgam MO or DO	28.1%	18.9%	39.6%	14.6%	16.1%	14.7%	26.9%
	1404 Amalgam MOD	11.2%	5.4%	6.8%	33.0%	8.0%	16.1%	14.1%
	1421 Resin Composite	5.6%	8.1%	4.9%	4.4%	41.4%	2.8%	7.9%

	1426 Glass Ionomer	6.7%		7.3%	3.9%	9.2%	32.2%	**10.0%**
	Crowns/Inlays	10.1%	8.1%	9.6%	12.1%	9.2%	11.2%	**10.3%**
	Extractions	4.5%	13.5%	11.0%	12.1%	4.6%	6.3%	**9.5%**
	Stoning	9.0%	2.7%	7.0%	7.3%	3.4%	3.5%	**6.3%**
	Other	2.2%	5.4%	5.6%	5.3%	2.3%	4.9%	**4.9%**
Total number (= 100%)		89	37	427	206	87	143	989

Table 4.33 Re-intervention type: tooth position 7

	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	**1401 Amalgam one surface**	32.9%	8.0%	4.1%	3.3%	8.3%	3.4%	**7.7%**
	1402 Amalgam two surface	2.7%	20.0%	3.0%	2.2%		1.1%	**3.1%**
	1403 Amalgam MO or DO	26.0%	36.0%	45.9%	12.1%	25.0%	26.1%	**34.0%**
	1404 Amalgam MOD	1.4%	12.0%	7.1%	28.6%	2.8%	6.8%	**9.5%**
	1421 Resin Composite	6.8%		4.7%	2.2%	41.7%	4.5%	**6.6%**
	1426 Glass Ionomer	5.5%		5.4%	6.6%	5.6%	36.4%	**9.9%**
	Crowns/Inlays	8.2%	4.0%	8.1%	17.6%	2.8%	5.7%	**8.7%**
	Extractions	11.0%	16.0%	12.8%	14.3%	2.8%	10.2%	**12.0%**
	Stoning	5.5%	4.0%	4.7%	7.7%	2.8%	1.1%	**4.6%**
	Other			4.1%	5.5%	8.3%	4.5%	**3.9%**
Total number (= 100%)		73	25	296	91	36	88	609

Table 4.34 Re-intervention type: tooth position 8

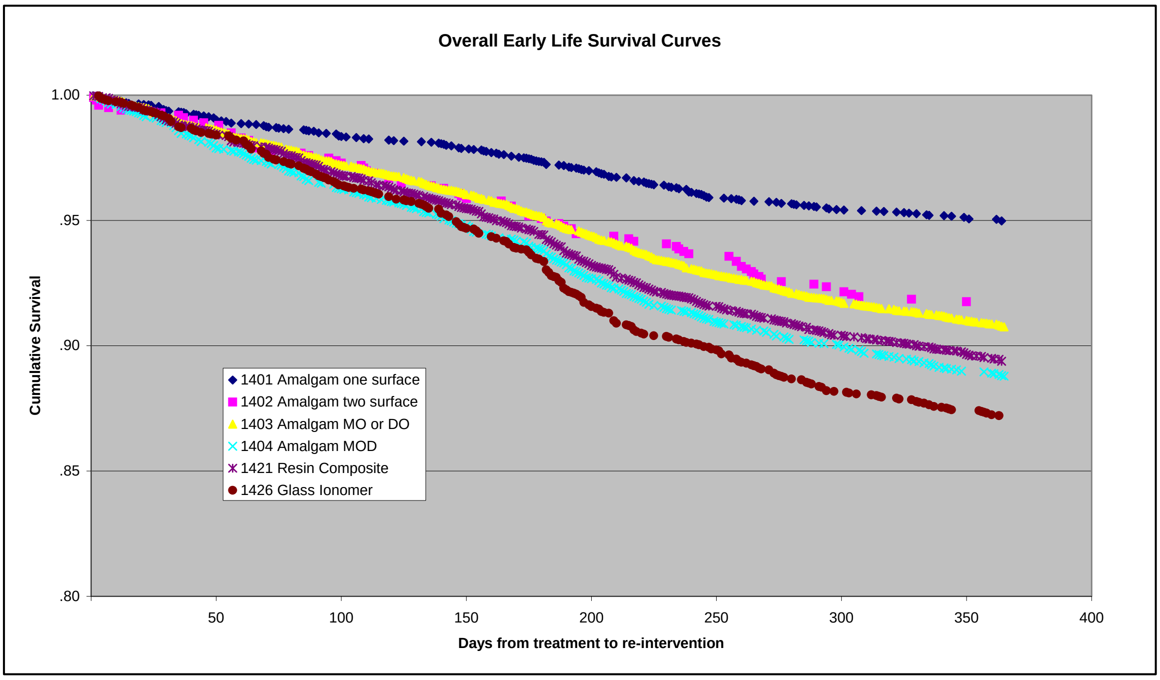
	Original Treatment Code	1401	1402	1403	1404	1421	1426	Overall
Type of Re-intervention	**1401 Amalgam one surface**	30.3%	7.7%	6.0%	7.1%	16.7%		**12.3%**
	1402 Amalgam two surface	15.2%	23.1%	6.0%				**8.5%**
	1403 Amalgam MO or DO	9.1%	38.5%	34.0%	14.3%	33.3%	21.4%	**24.6%**
	1404 Amalgam MOD			6.0%	7.1%			**3.1%**
	1421 Resin Composite	3.0%		8.0%	7.1%	50.0%	7.1%	**7.7%**
	1426 Glass Ionomer	6.1%		8.0%	7.1%		35.7%	**9.2%**
	Crowns/Inlays			8.0%	7.1%		7.1%	**4.6%**
	Extractions	30.3%	30.8%	20.0%	35.7%		21.4%	**24.6%**
	Stoning	6.1%		2.0%	14.3%		7.1%	**4.6%**
	Other			2.0%				**.8%**
Total number (= 100%)		33	13	50	14	6	14	130

Molar teeth experienced all six types of restorations, although glass ionomer and composite resin restorations were restricted to class V cavities. Again, the most common re-intervention, around 30%, was the same as the original, though single surface amalgams were often retreated with MO or DO amalgams. First and second molar teeth were similar, with about 10% retreated with crowns or inlays and about 10% with extractions. Third molars had a much higher extraction rate, around 25%, with only about 5% being followed by a crown or inlay.

4.1.5 First Year Survival Time Curves

From the preceding sections it is apparent that the association between tooth position and treatment type is important. The chart (Figure 4.1) shows, in summary, the Kaplan-Meier estimates for the empirical survivor function over the first year. Each point on the chart corresponds to one or more re-interventions on a tooth previously treated with a particular type of filling. Similar charts can be found in the appendix for each of the eight tooth positions.

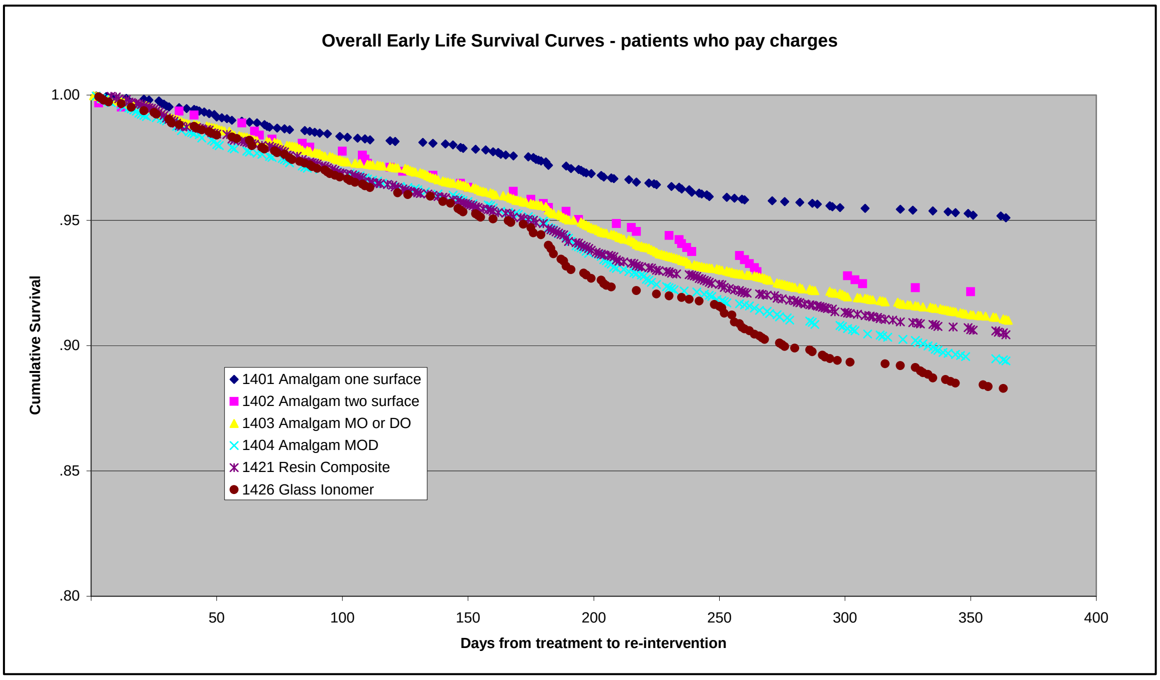
Figure 4.1 One year survival – overall for patients born in 1965



Overall, there was clearly a systematic difference between the survival behaviour of the six different types of restoration. This was confirmed by pairwise log-rank tests, where all comparisons bar those between 1402 and 1403, 1404 and 1421, and 1404 and 1426 were significant ($p<0.05$). Although the overall curves appear smooth and they fan out consistently, there does appear to be an inflexion at around 180 days. This is particularly marked for glass ionomer fillings.

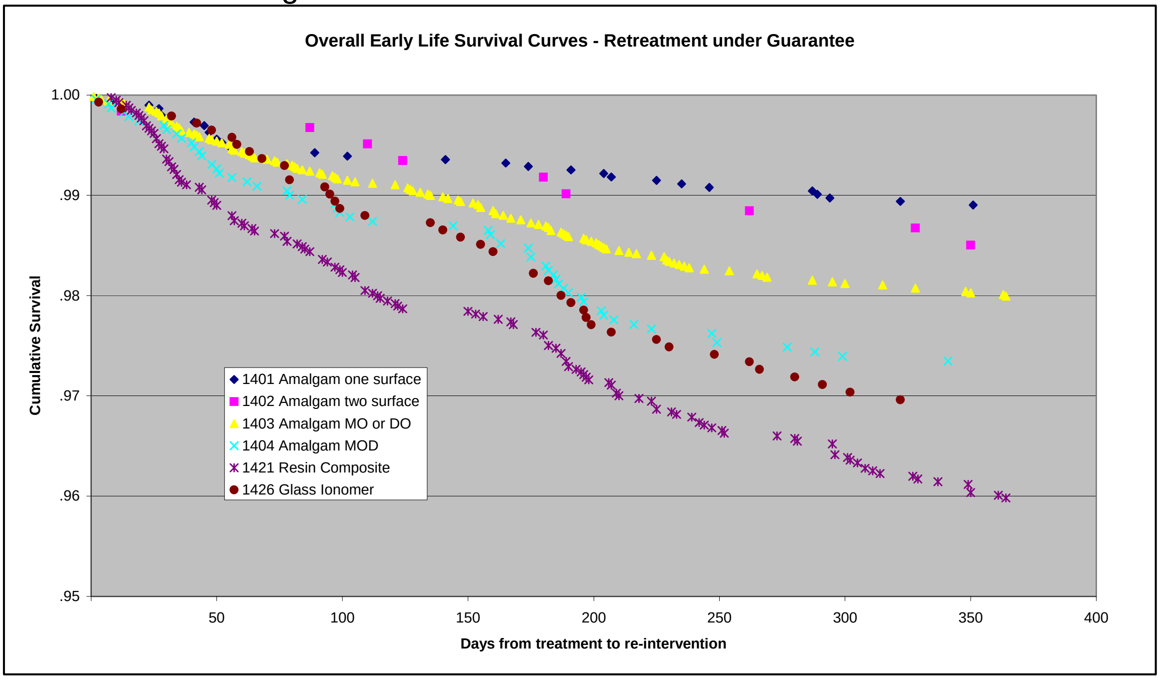
Finally, the following analysis considers whether replacement under guarantee distorted the pattern of re-intervention. Figure 4.2 is restricted to patients who paid full charges (the only patients for whom the guarantee is needed, since other patients get free replacement treatment anyway), and it can be seen the pattern is similar to that for all patients (Figure 4.1), at least in the relative position of the different types of restoration.

Figure 4.2 One year survival – patients born in 1965 – charge-payers



If the outcome is now restricted to re-intervention under guarantee, and other re-interventions are treated as censored, then the pattern in Figure 4.3 emerges. Note the change of vertical scale – only a small proportion of re-interventions within one year were in fact claimed under guarantee.

Figure 4.3 One year survival - patients born in 1965 - retreatment under guarantee



4.1.6 Control Analyses

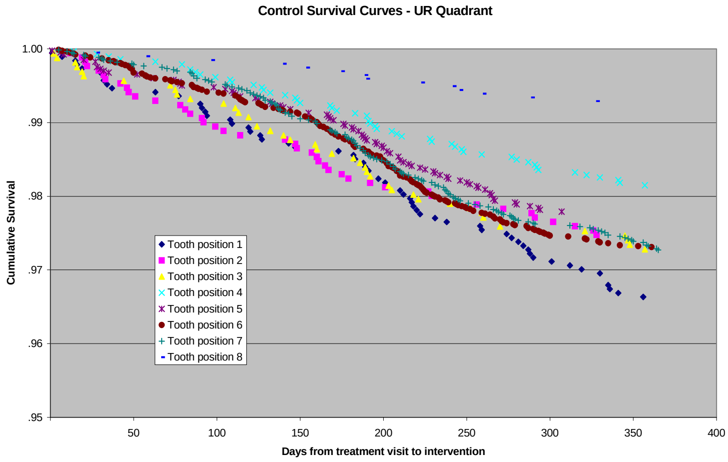
As a control analysis, the times to first treatment of the teeth in the same position but different quadrants in the same patient, were used as an indicator of the expected survival time without treatment.

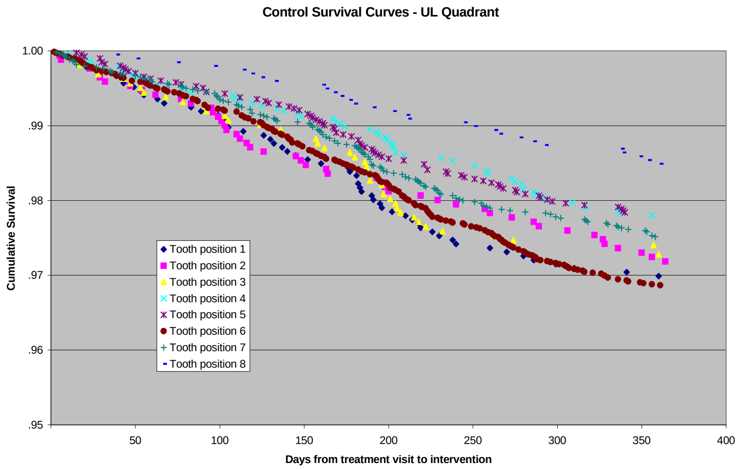
For each patient and tooth position for which a restoration was placed in the March 2000 payment schedule a dummy record was created with the same details, except for quadrant, as the restoration record. This dummy record was then processed as though it had received a restoration at the same time as the corresponding tooth that had actually received a restoration. For most actual restorations three such dummy records were created. A Kaplan-Meier analysis was carried out looking at all subsequent treatments of the tooth positions of the dummy records. The results are summarized as a set of charts (Figure 4.4)

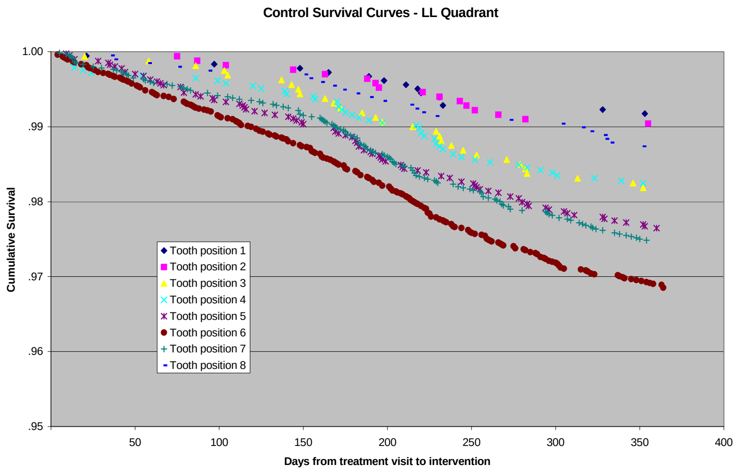
The main point to note is that irrespective of tooth position, the treatment rate within one year of a treatment in another tooth in the same position but a different quadrant remained less than about three per cent. There was clear lateral symmetry, but a noticeable difference between upper and lower jaws. On the lower jaw first molars were most likely to be treated, and incisors least likely. On the upper jaw both first molars and incisors, particularly central incisors, were most likely to receive treatment, while upper third molars were least likely to be treated. The treatment showed broad patterns for type of treatment and sex of patient similar to those for restorations recorded in the March 2000 schedule– as can be seen from the tables in the appendix.

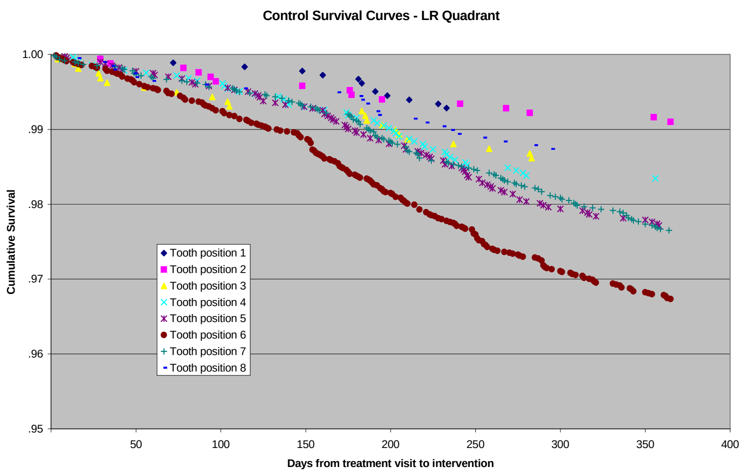
Females were marginally more likely overall to have treatments than males (around 0.2 of a percentage point), though this reflects some variation between tooth positions.

Figure 4.4 Control Survival Curves – by quadrant









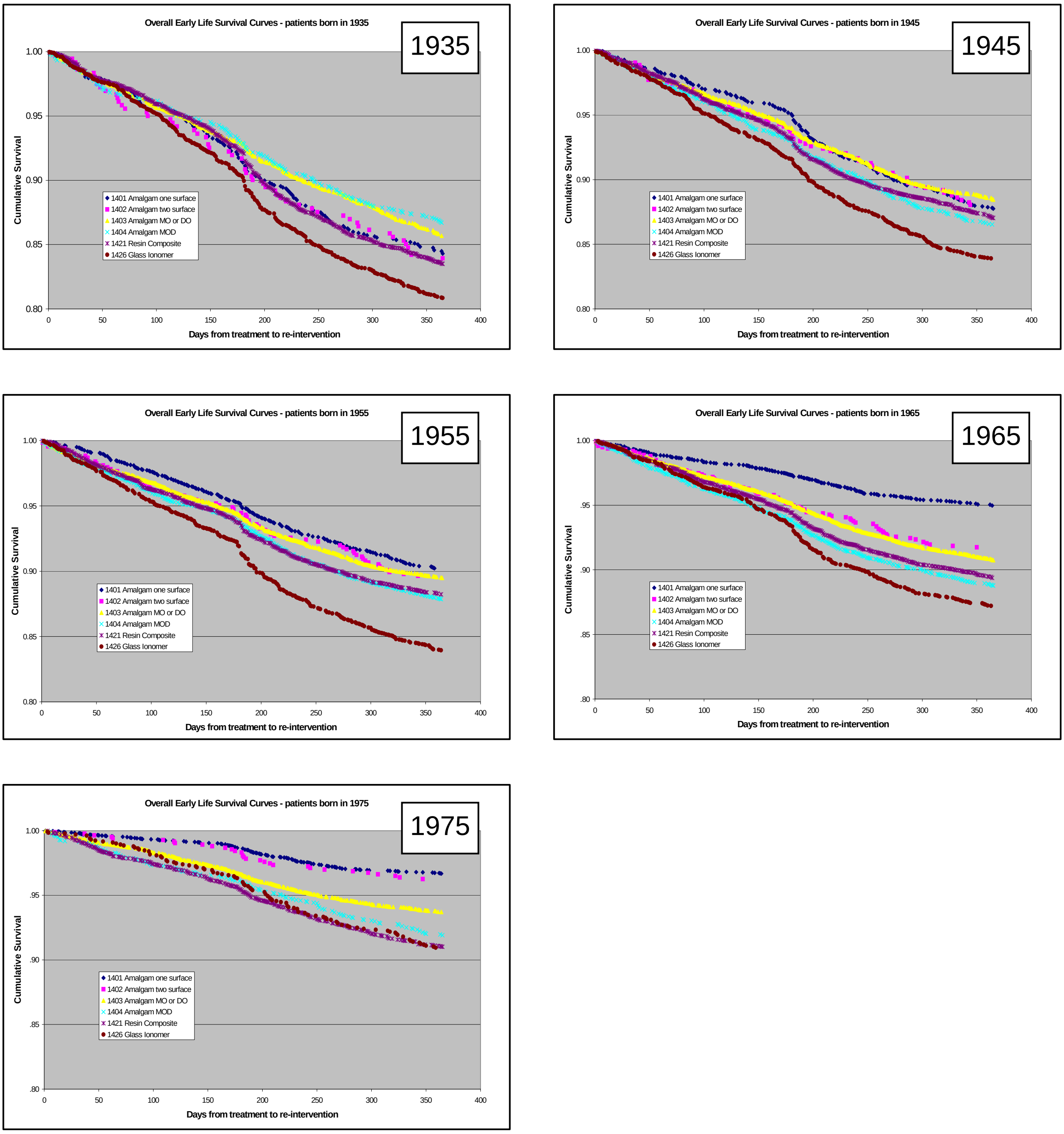
4.1.7 Highlights of Analyses for Other Age Groups

The full analysis described in sections 4.1.1 to 4.1.6 has been repeated for four other age groups: patients born in 1935, 1945, 1955, and 1975. The full detail is available in the appendix and this section provides only an overview.

Table 4.35 Number of restorations included in early life analysis

	Number of restorations placed in March 2000 Schedule					
Patient Year of Birth	1975	1965	1955	1945	1935	
Age in 2000	35	45	55	65	75	**Total**
Type of restoration						
1401	5,238	4,839	2,426	1,765	1,128	**15,396**
1402	828	994	686	527	361	**3,396**
1403	7,486	11,221	7,443	4,803	2,873	**33,826**
1404	1,867	3,930	3,677	2,645	1,520	**13,639**
1421	4,329	7,663	6,919	7,807	6,471	**33,189**
1426	1,303	3,010	3,055	3,288	3,107	**13,763**
Total	**21,051**	**31,657**	**24,206**	**20,835**	**15,460**	**113,209**

Figure 4.5 One-year survival curves by age cohort of patient



It was generally found that most of the findings for the 1965 cohort also applied to patients of other ages, albeit with some adjustment to scale. In general, the older the patient the more likely that a tooth would receive a re-intervention within one year. To illustrate this, Figure 4.5 gives the summary charts for all five age groups, starting with the oldest, those born in 1935.

The differentiation between the six types of restoration was greatest for patients born in 1955 and 1965, with the oldest and youngest patients showing least variation. The order of the different types was similar for all ages, with the exception of 1401 (single surface amalgam) and 1404 (MOD amalgam), which systematically got closer with increasing patient age, to the extent that the two curves overlapped for the oldest patients.

Figure 4.6 Patient age and type of re-intervention

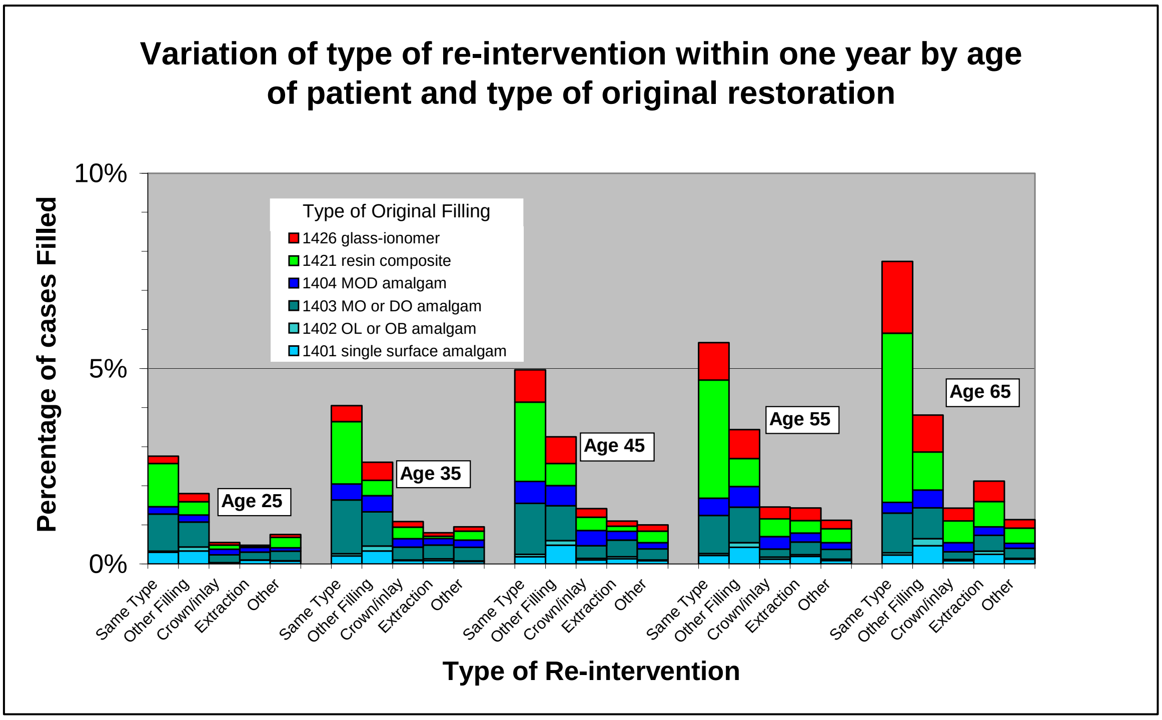


Figure 4.6 provides a summary of the volumes and patterns of re-intervention for the five different age groups. Each column in the chart represents, for a particular age group, the proportion of restorations with that type of re-intervention within one year, subdivided by the original type of restoration.

4.2 Cross-sectional Analysis

4.2.1 Kaplan-Meier – by Treatment Type

The source data consist of the records of all teeth treated during the thirteen months ending on April 30th 2001 for GDS patients who were born in the year 1965. The data were drawn from the database in January 2002, so that a long period had been allowed for the accumulation of any data submitted late. From this set of data were derived a set of restoration ‘lives’, each record containing the date on which a filling was placed and the date, if any, on which the same tooth was next treated with a treatment which implied that the original filling is likely to have been replaced or removed. These treatments comprised further fillings, crowns and extractions, but not stoning and smoothing, which imply that the filling remained in place.

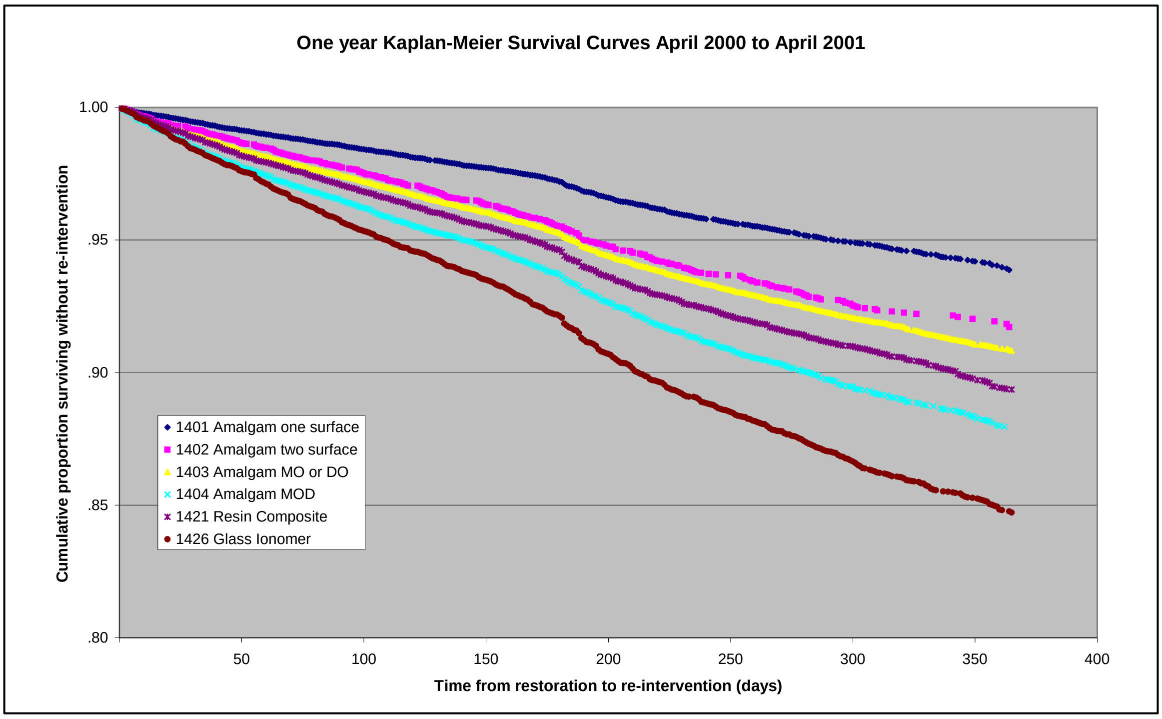
The total number of cases included in the derived dataset was 364,124. Of these, the total number of filled teeth with re-intervention in the whole period, and hence the number of completed ‘lives’ included in the study, was 20,873. The distribution between the different types of filling is shown in Table 4.36.

Table 4.36 Distribution by type of restoration April 2000 to April 2001 - patients born in 1965

Restoration Type	Restorations Placed	Re-interventions
1401	52,771	1,764
1402	11,693	568
1403	128,057	6,782
1404	44,335	3,114
1421	92,845	5,608
1426	34,423	3,037
Total	**364,124**	**20,873**

To give reference curves (Figure 4.7), standard Kaplan-Meier analysis was applied to the set of restoration lives, using the SPSS statistical package, and treating filled teeth for which there were no subsequent treatments as censored after 365 days or at the end of April 2001, whichever came earlier.

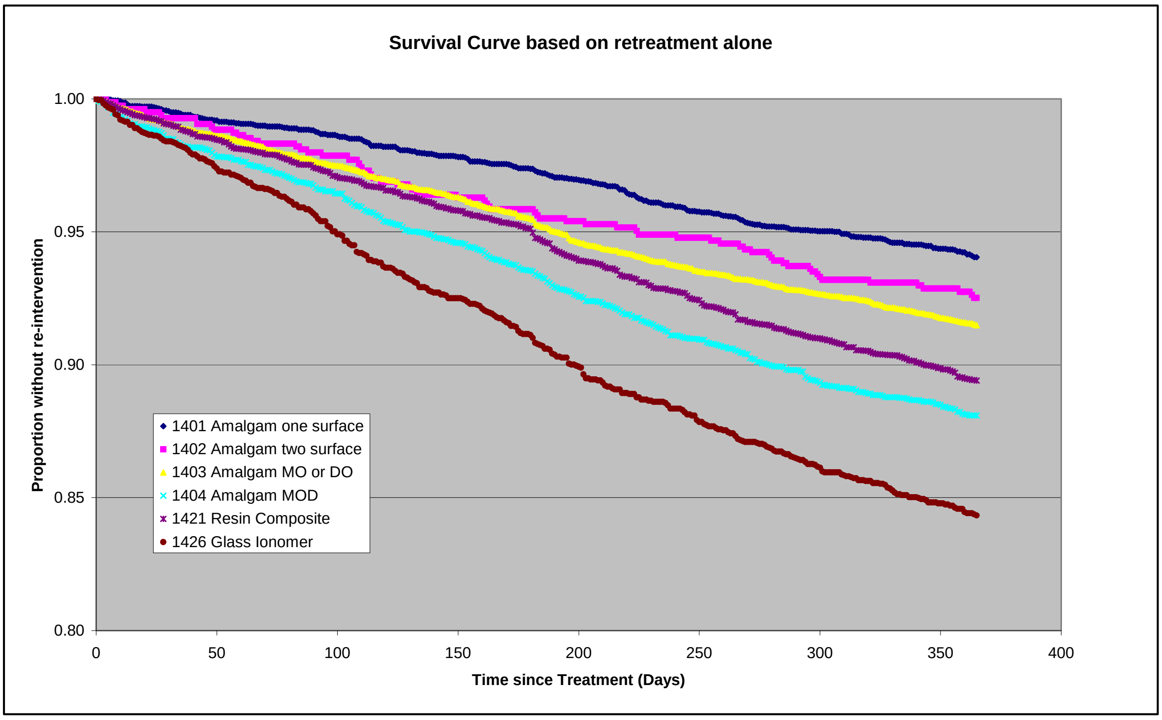
Figure 4.7 Kaplan-Meier survival curves for restorations placed between April 2000 and April 2001 inclusive



4.2.2 Retreated Teeth – by Original Treatment Type

In the month of April 2001, the number of teeth retreated was 2,677. Figure 4.8 shows the estimated survival curves based only on treatment carried out during the cross-sectional period (April 2001).

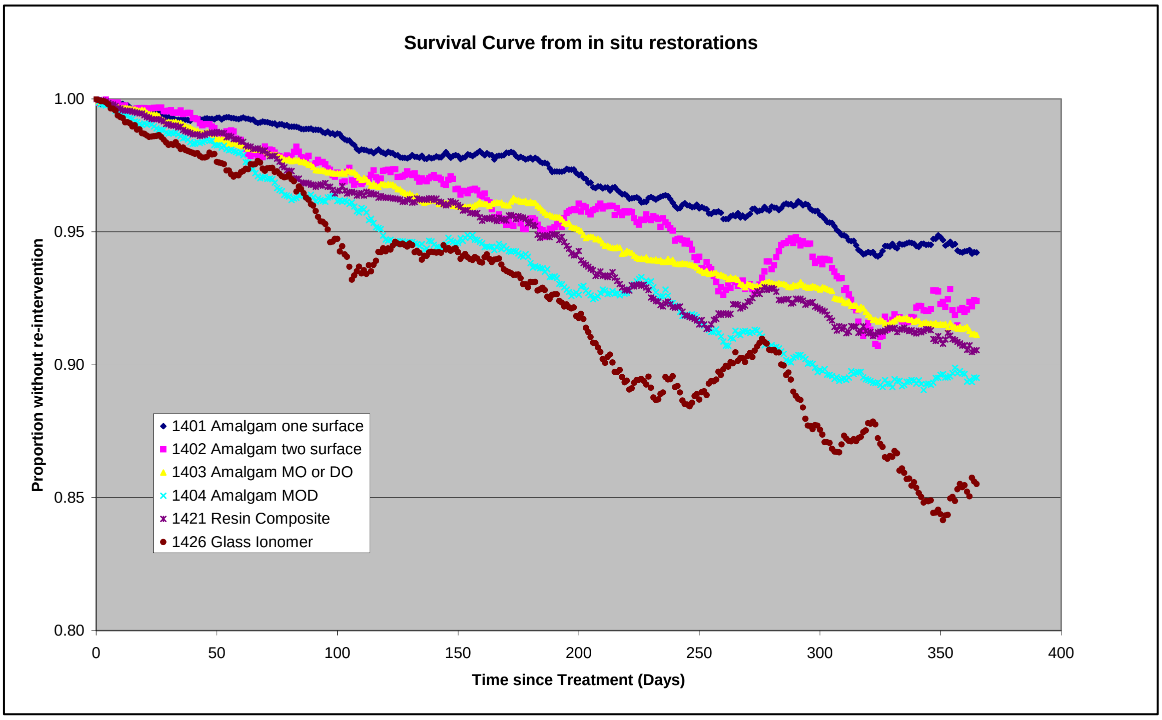
Figure 4.8 Survival curves based on cross-sectional treatment alone



4.2.3 Restorations *In Situ* – by Treatment Type

The average number of restorations *in situ* in April 2001 was 321,212, restricted to cases where the filling had been placed within the preceding 365 days. Figure 4.9 shows the estimated survival curves using only data for teeth with restorations *in situ* during the cross-sectional period.

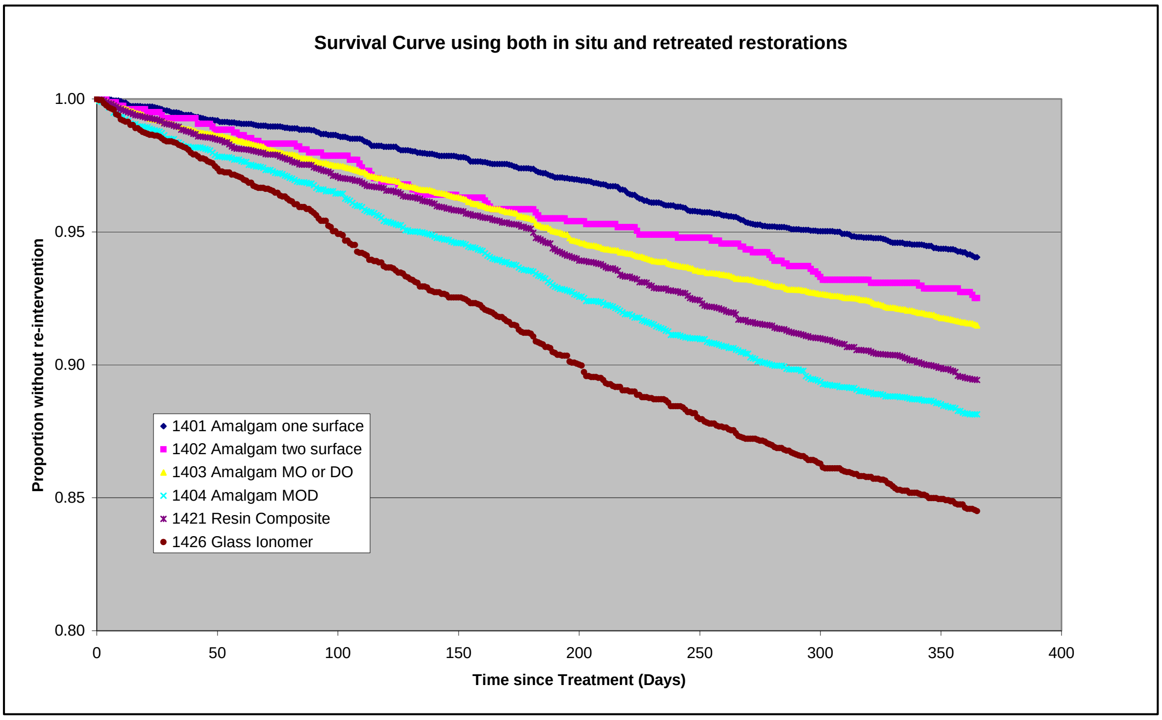
Figure 4.9 Survival curves based on restorations *in situ* at cross-section



4.2.4 Combined Retreated Teeth and Restorations *In Situ* – by Treatment Type

The data for this analysis (Figure 4.10) consist of the restorations *in situ* in April 2001 – averaging 321,212 – plus the 2,677 which had re-intervention during April 2001, but excluding those which were no longer *in situ* at the beginning of April (but including restorations placed during April).

Figure 4.10 Survival curves derived from a combination of restorations *in situ* and those with re-intervention at cross-section



4.2.5 Comparison of All Four Methods

Figure 4.11 Comparison of survival curves for Kaplan-Meier and three cross-sectional methods

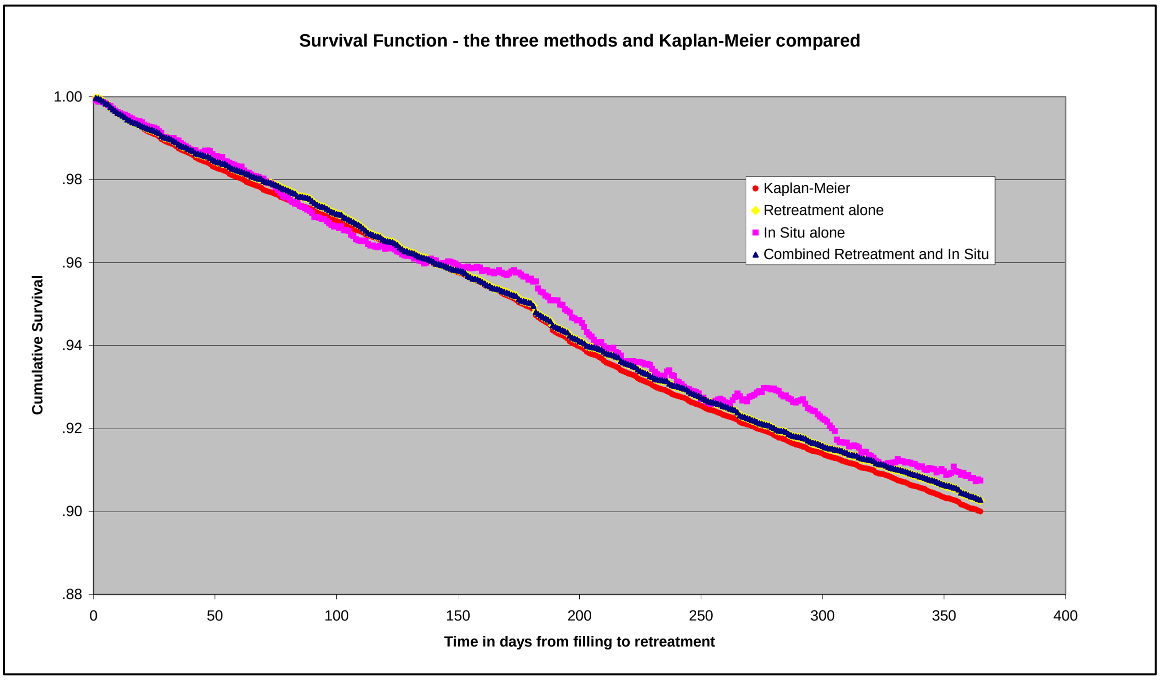


Figure 4.11 shows, on a single chart, the differences between the three cross-sectional estimated survival curves and the reference Kaplan-Meier empirical survival curve based on all restorations placed in the observation period (April 2000 to April 2001, inclusive), including those which had re-interventions before the cross-section (April 2001).

4.3 Full Longitudinal Analysis

4.3.1 Characteristics of the Sample Population for Full Longitudinal Analysis

Table 4.37 provides an overview of the patients and courses of treatment contained in the complete set of sample data covering all claims scheduled between January 1991 and March 2002, inclusive. Just over eighty thousand different adult patients were identified, of whom 46% were male and 54% female. Between them they accounted for 719 thousand claims. There was a wide variation in the number of claims associated with each patient. Thirteen per cent of patients appeared in the records only once, but they accounted for only one per cent of the claims. On the other hand, those one per cent of patients who appeared thirty times or more accounted for five per cent of the claims.

Table 4.37 Whole eleven year sample – patients by number of claims and patient sex

Summary of all claims for all patients in 11 year sample

Number of Claims	Patient sex		Number of Patients	% of patients	Number of Claims	% of claims
	Female	Male				
1	5,103	5,253	10,356	13%	10,356	1%
2	3,942	3,953	7,895	10%	15,790	2%
3	3,491	3,421	6,912	8%	20,736	3%
4	3,112	2,882	5,994	7%	23,976	3%
5	2,822	2,507	5,329	6%	26,645	4%
6	2,512	2,108	4,620	6%	27,720	4%
7	2,226	1,826	4,052	5%	28,364	4%
8	2,048	1,753	3,801	5%	30,408	4%
9	1,898	1,512	3,410	4%	30,690	4%
10	1,752	1,388	3,140	4%	31,400	4%
11	1,588	1,227	2,815	3%	30,965	4%
12	1,420	1,184	2,604	3%	31,248	4%
13	1,414	1,013	2,427	3%	31,551	4%
14	1,259	970	2,229	3%	31,206	4%
15	1,145	854	1,999	2%	29,985	4%
16	1,098	782	1,880	2%	30,080	4%
17	1,030	796	1,826	2%	31,042	4%
18	943	652	1,595	2%	28,710	4%
19	919	646	1,565	2%	29,735	4%
20	845	589	1,434	2%	28,680	4%
21	770	552	1,322	2%	27,762	4%
22	671	434	1,105	1%	24,310	3%
23	512	373	885	1%	20,355	3%
24	372	267	639	1%	15,336	2%
25	288	224	512	1%	12,800	2%
26	242	138	380	0%	9,880	1%
27	194	141	335	0%	9,045	1%
28	165	103	268	0%	7,504	1%
29	130	84	214	0%	6,206	1%
30 or more	636	358	994	1%	36,524	5%
Total	**44,547**	**37,990**	**82,537**		**719,009**	

Table 4.37 should be contrasted with Table 4.38 which gives the corresponding figures when the analysis was restricted to claims which contained direct placed restorations and which had a latest recorded date before 1st January 2002. Nearly all the patients in the first table (80,433 out of 82,537) appear in the second. The distribution of claims with fillings was much tighter than that for all claims, with two thirds of the patients being the subject

of only three or fewer filling claims. It is, however, clear that most of the 35% who appeared on only one filling claim were also the subject of other claims. A total of 270 thousand claims contained direct restorations, and again some 54% of the patients were female.

Table 4.38 Eleven-year sample – restricted to claims which contained direct restorations

Summary of all claims containing direct restorations in eleven year sample

Number of Claims	Patient sex		Number of Patients	% of patients	Number of Claims	% of claims
	Female	Male				
1	14,702	13,082	27,784	35%	27,784	10%
2	8,289	7,238	15,527	19%	31,054	11%
3	5,518	4,741	10,259	13%	30,777	11%
4	4,009	3,295	7,304	9%	29,216	11%
5	2,959	2,306	5,265	7%	26,325	10%
6	2,124	1,709	3,833	5%	22,998	9%
7	1,504	1,296	2,800	3%	19,600	7%
8	1,093	921	2,014	3%	16,112	6%
9	864	697	1,561	2%	14,049	5%
10	629	513	1,142	1%	11,420	4%
11	439	351	790	1%	8,690	3%
12	306	293	599	1%	7,188	3%
13	217	198	415	1%	5,395	2%
14	168	138	306	0%	4,284	2%
15	136	110	246	0%	3,690	1%
16	81	67	148	0%	2,368	1%
17	67	50	117	0%	1,989	1%
18	40	23	63	0%	1,134	0%
19	34	31	65	0%	1,235	0%
20	26	28	54	0%	1,080	0%
21	25	21	46	0%	966	0%
22	14	15	29	0%	638	0%
23	5	6	11	0%	253	0%
24	7	5	12	0%	288	0%
25	11	3	14	0%	350	0%
26	3	3	6	0%	156	0%
27	6	2	8	0%	216	0%
28	2	2	4	0%	112	0%
29	3	4	7	0%	203	0%
30 or more	10	4	14	0%	546	0%
Total	**43,291**	**37,152**	**80,443**		**270,116**	

Table 4.39 shows how these 270 thousand claims containing directly placed restorations were distributed between male and female patients by age group.

The highest proportions of claims of this type related to patients in their thirties and forties. Except for the 60 to 69 age group, there were always more female patients than males.

Table 4.39 Analysis of filling claims by patient age and sex

Claims containing at least one directly placed restoration						
		Patient sex		Total	Percent
		Female	Male		
Patient age (years)	18 or 19	3,221	2,805	6,026	2%
	20 to 29	25,863	19,436	45,299	17%
	30 to 39	35,303	27,323	62,626	23%
	40 to 49	32,708	27,309	60,017	22%
	50 to 59	24,145	21,148	45,293	17%
	60 to 69	15,113	15,579	30,692	11%
	70 to 79	8,230	7,979	16,209	6%
	80 or older	2,395	1,559	3,954	1%
Total		**146,978**	**123,138**	**270,116**	**100%**

Table 4.39 should be compared with Table 4.40, which shows the corresponding analysis for individual teeth restored. The dominance of females over males was not so great, and for patients aged 18 or 19, 60 to 69 and 70 to 79 more male teeth were restored with fillings than female teeth. This implies a higher number of teeth filled per visit, on average, for male patients compared with females.

Table 4.40 Analysis of teeth filled by patient age and sex

Teeth treated with directly placed restorations					
		Patient sex		Total	Percent
		Female	Male		
Patient age (years)	18 or 19	11,991	12,026	24,017	3%
	20 to 29	96,086	83,329	179,415	21%
	30 to 39	108,371	94,133	202,504	24%
	40 to 49	91,531	83,822	175,353	21%
	50 to 59	65,503	62,087	127,590	15%
	60 to 69	38,687	43,129	81,816	10%
	70 to 79	20,951	21,193	42,144	5%
	80 or older	6,424	4,631	11,055	1%
Total		**439,544**	**404,350**	**843,894**	**100%**

Table 4.41 Teeth filled – position in the mouth

Numbers of teeth filled by tooth position and quadrant						
		Mouth quadrant				Total
		LL	LR	UL	UR	
Tooth position	1	6,826	6,501	28,458	28,140	**69,925**
	2	7,376	6,890	24,884	24,114	**63,264**
	3	11,721	11,041	26,750	25,123	**74,635**
	4	21,498	21,064	29,176	30,933	**102,671**
	5	30,447	30,477	31,485	31,932	**124,341**
	6	45,474	45,814	48,166	46,848	**186,302**
	7	43,249	42,206	42,447	40,062	**167,964**
	8	15,564	14,285	12,784	12,159	**54,792**
Total		**182,155**	**178,278**	**244,150**	**239,311**	**843,894**

Table 4.41 shows how these filled teeth were distributed about the patients' mouths. Except for second and third molars there were generally higher numbers of restorations placed on teeth in the upper jaw, particularly for incisor and canine teeth.

Table 4.42 Type of filling by age of patient - females

Frequency of different types of direct restoration by patient age – female patients										
	Patient Age	18 or 19	20 to 29	30 to 39	40 to 49	50 to 59	60 to 69	70 to 79	80 or older	Total
Main Treat-ment	Single surface amalgam	4,238	25,188	16,749	10,152	6,112	3,329	1,818	480	**68,066**
	Two surface amalgam, not MO or DO	579	3,980	3,577	2,753	1,765	942	459	127	**14,182**
	MO or DO amalgam	3,761	33,772	38,027	27,395	15,472	7,150	3,017	782	**129,376**
	MOD amalgam	696	9,053	14,648	13,746	8,538	4,150	1,419	347	**52,597**
	Tunnel amalgam	37	115	52	23	9	9	4		**249**
	Composite resin	1,853	15,921	22,628	23,761	21,375	14,850	8,664	2,458	**111,510**
	Glass ionomer	612	6,006	9,928	11,142	10,591	7,461	5,216	2,155	**53,111**
	Root filling	215	2,051	2,762	2,559	1,641	796	354	75	**10,453**
Total		**11,991**	**96,086**	**108,371**	**91,531**	**65,503**	**38,687**	**20,951**	**6,424**	**439,544**

Table 4.43 Type of filling by age of patient - males

Frequency of different types of direct restoration by patient age –male patients										
	Patient Age	**18 or 19**	**20 to 29**	**30 to 39**	**40 to 49**	**50 to 59**	**60 to 69**	**70 to 79**	**80 or older**	**Total**
Main Treat-ment	**Single surface amalgam**	4,027	22,257	16,282	9,984	6,213	3,921	2,228	458	**65,370**
	Two surface amalgam, not MO or DO	630	3,744	3,267	2,578	1,771	1,060	590	124	**13,764**
	MO or DO amalgam	3,689	28,712	32,751	26,035	15,693	8,889	3,269	544	**119,582**
	MOD amalgam	752	7,680	12,547	12,202	7,665	4,055	1,417	231	**46,549**
	Tunnel amalgam	28	75	59	46	17	18	2		**245**
	Composite resin	2,013	13,991	19,098	20,660	18,725	15,454	8,026	1,747	**99,714**
	Glass ionomer	621	4,701	7,582	10,133	10,492	8,766	5,286	1,459	**49,040**
	Root filling	266	2,169	2,547	2,184	1,511	966	375	68	**10,086**
Total		**12,026**	**83,329**	**94,133**	**83,822**	**62,087**	**43,129**	**21,193**	**4,631**	**404,350**

Table 4.42 and Table 4.43 show, for females and males respectively, the distribution of the different types of filling according to the age group of the patient. The groupings include ‘occasional’ treatment codes along with the usual (1401, 1402, etc) codes, since the treatment provided is the same. Root fillings and tunnel restorations have also been separately identified, although it should be noted that the classification of each tooth filled was by ‘main’ treatment in the order listed in the table, so that a tooth was classified as having a root filling as the main treatment only when no other directly placed restoration was present. In effect, the only teeth classified as root filled in these tables were those accompanied by indirect restorations such as crowns and inlays. Table 4.44 provides the totals across all patients.

Table 4.44 Type of filling by age of patient – all patients

Frequency of different types of direct restoration by patient age – all patients										
	Patient Age	**18 or 19**	**20 to 29**	**30 to 39**	**40 to 49**	**50 to 59**	**60 to 69**	**70 to 79**	**80 or older**	**Total**
Main Treat-ment	**Single surface amalgam**	8,265	47,445	33,031	20,136	12,325	7,250	4,046	938	**133,436**
	Two surface amalgam, not MO or DO	1,209	7,724	6,844	5,331	3,536	2,002	1,049	251	**27,946**
	MO or DO amalgam	7,450	62,484	70,778	53,430	31,165	16,039	6,286	1,326	**248,958**
	MOD amalgam	1,448	16,733	27,195	25,948	16,203	8,205	2,836	578	**99,146**
	Tunnel amalgam	65	190	111	69	26	27	6	-	**494**
	Composite resin	3,866	29,912	41,726	44,421	40,100	30,304	16,690	4,205	**211,224**
	Glass ionomer	1,233	10,707	17,510	21,275	21,083	16,227	10,502	3,614	**102,151**
	Root filling	481	4,220	5,309	4,743	3,152	1,762	729	143	**20,539**
Total		**24,017**	**179,415**	**202,504**	**175,353**	**127,590**	**81,816**	**42,144**	**11,055**	**843,894**

4.3.2 Robustness of Adjustment Method

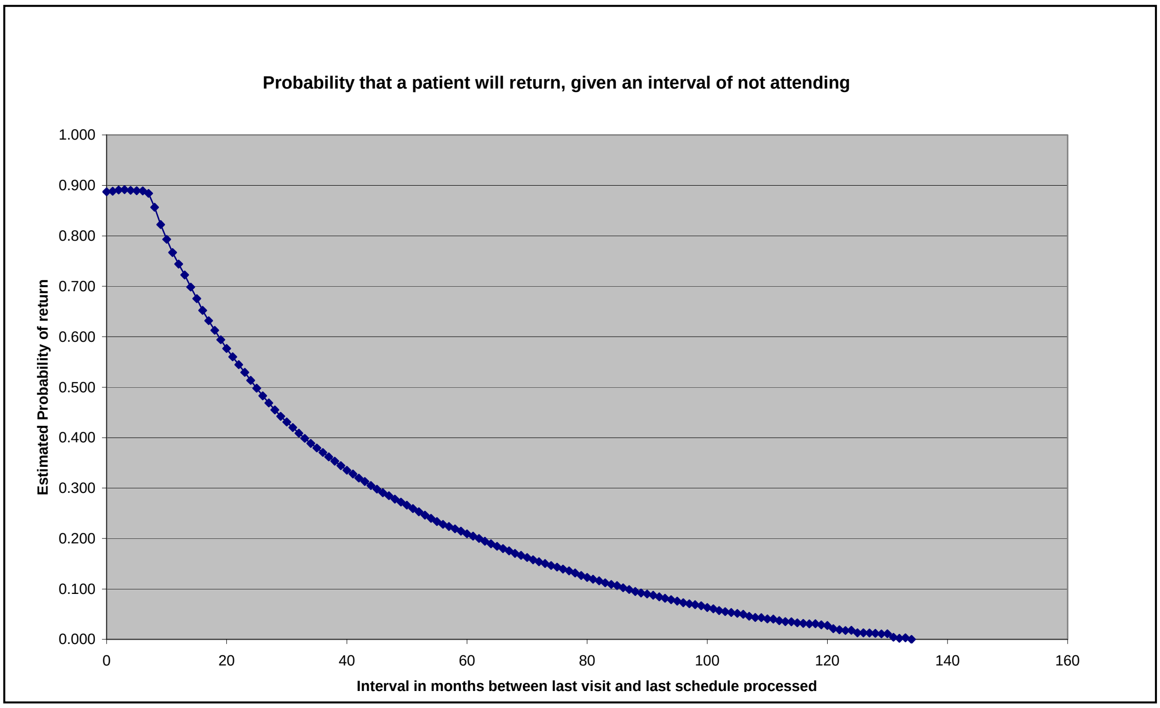
In this section the method of estimating the probability of re-attendance is worked through, the plausibility of the assumption that few patients will eventually re-attend if they have not been seen for several years is tested, the extent to which other factors may be associated with probability of eventual re-attendance is explored, and the sensitivity of the resulting survival curves to different assumptions about censoring dates is demonstrated. Finally, alternative methods of estimating standard errors are compared.

Table 4.45 is an abbreviated example of a frequency table using the methodology described in section 3.4.1. The results are plotted in Figure 4.12.

Table 4.45 Probability of patient re-attendance

	Frequency over all courses			Claims Remaining			
Interval	No revisit	Revisited	Total	No revisit	Revisit	Total	Pr(revisit)
0	1,009	1,117	2,126	82,537	649,849	732,386	0.887
1	4,005	16,450	20,455	81,528	648,732	730,260	0.888
2	5,039	34,894	39,933	77,523	632,282	709,805	0.891
3	3,669	38,998	42,667	72,484	597,388	669,872	0.892
4	4,845	42,783	47,628	68,815	558,390	627,205	0.890
5	4,407	37,886	42,293	63,970	515,607	579,577	0.890
6	3,540	49,524	53,064	59,563	477,721	537,284	0.889
7	2,602	108,691	111,293	56,023	428,197	484,220	0.884
8	2,256	82,270	84,526	53,421	319,506	372,927	0.857
9	1,890	48,283	50,173	51,165	237,236	288,401	0.823
10	1,597	31,891	33,488	49,275	188,953	238,228	0.793
11	1,357	22,341	23,698	47,678	157,062	204,740	0.767
12	1,291	17,499	18,790	46,321	134,721	181,042	0.744
...	...	...	...	...	...	...	...
125	241	3	244	1,961	26	1,987	0.013
126	227	4	231	1,720	23	1,743	0.013
127	190	3	193	1,493	19	1,512	0.013
128	230	4	234	1,303	16	1,319	0.012
129	187	2	189	1,073	12	1,085	0.011
130	196	7	203	886	10	896	0.011
131	193	2	195	690	3	693	0.004
132	172		172	497	1	498	0.002
133	156	1	157	325	1	326	0.003
134	169		169	169	-	169	0.000
Total	82,537	649,849	732,386				

Figure 4.12 Probability of patient re-attendance



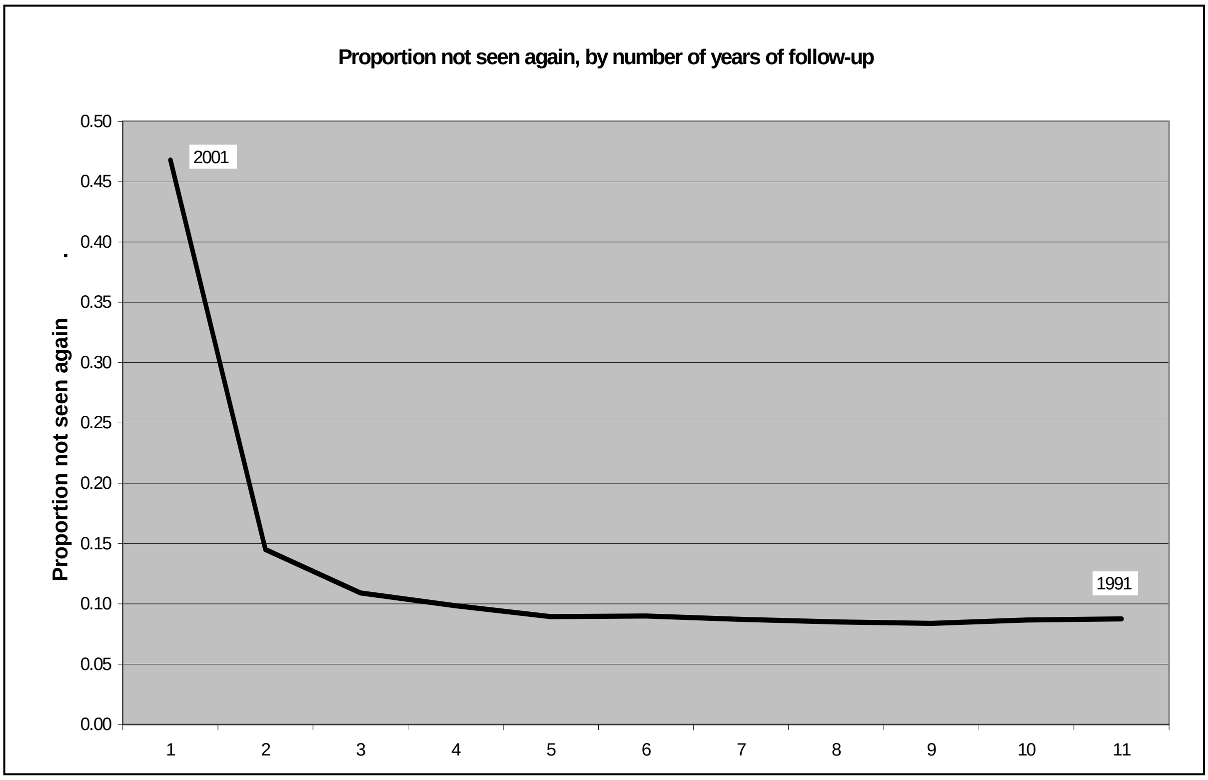
The chart (Figure 4.12) shows the empirical relationship between time interval from last attendance to last observed payment schedule and the proportion of remaining cases which involved re-attendance within the observed data. It can be seen that, for the first six months (seven including the time lag to production of the payment schedule), the interval provides little information about the likelihood of re-attendance. The rules of the GDS discourage re-attendance within six months because the dentist is not allowed to claim an examination fee until at least five months have elapsed. Even the most frequently attending patients therefore, are not expected to re-attend within this period. For that first six month period the estimated probability of eventual re-attendance is constant at the initial probability of re-attendance, of about 0.9. Thereafter however, the longer the gap, the less likely it is that a patient will re-attend, and hence the more likely that the survival time will be censored.

The method of estimating the relationship between follow-up period and probability of re-attendance expounded in section 3.4.1 depends on the full dataset, but the greater the interval the more the curve depends on the earlier data. The curve has been estimated across the whole population of courses of treatment, and it is of interest to know whether the curve varies appreciably between different sub-populations.

Accordingly, five additional analyses were carried out. The first explored the relationship between the number of years of follow-up and the proportion of patients who were not seen again. The second considered the geographical dichotomy between courses of treatment carried out in London surgeries and those carried out elsewhere. The third divided the courses into those where the patient paid full patient charges and those which involved exemption from or remission of patient charges. The fourth checked for differences according to the sex of the patient – for example because of change of name on marriage. Finally, the courses were divided according to patient age.

The analysis by year of last visit is complicated by the original definition of the population in the study. The restriction to courses undergone by patients who had received at least one course with a direct restoration would have biased the data from earlier years towards courses of treatment with a subsequent visit, since unless the first course of treatment was itself a course containing a direct restoration, the first course of treatment was, by definition of the population, guaranteed to have had another visit before the end of the observation period. Accordingly, for this analysis only, the population was extended to include all courses of treatment in the full DPB quarter percent sample, irrespective of the treatment involved.

Figure 4.13 Proportion of patients not seen again, by length of follow-up period

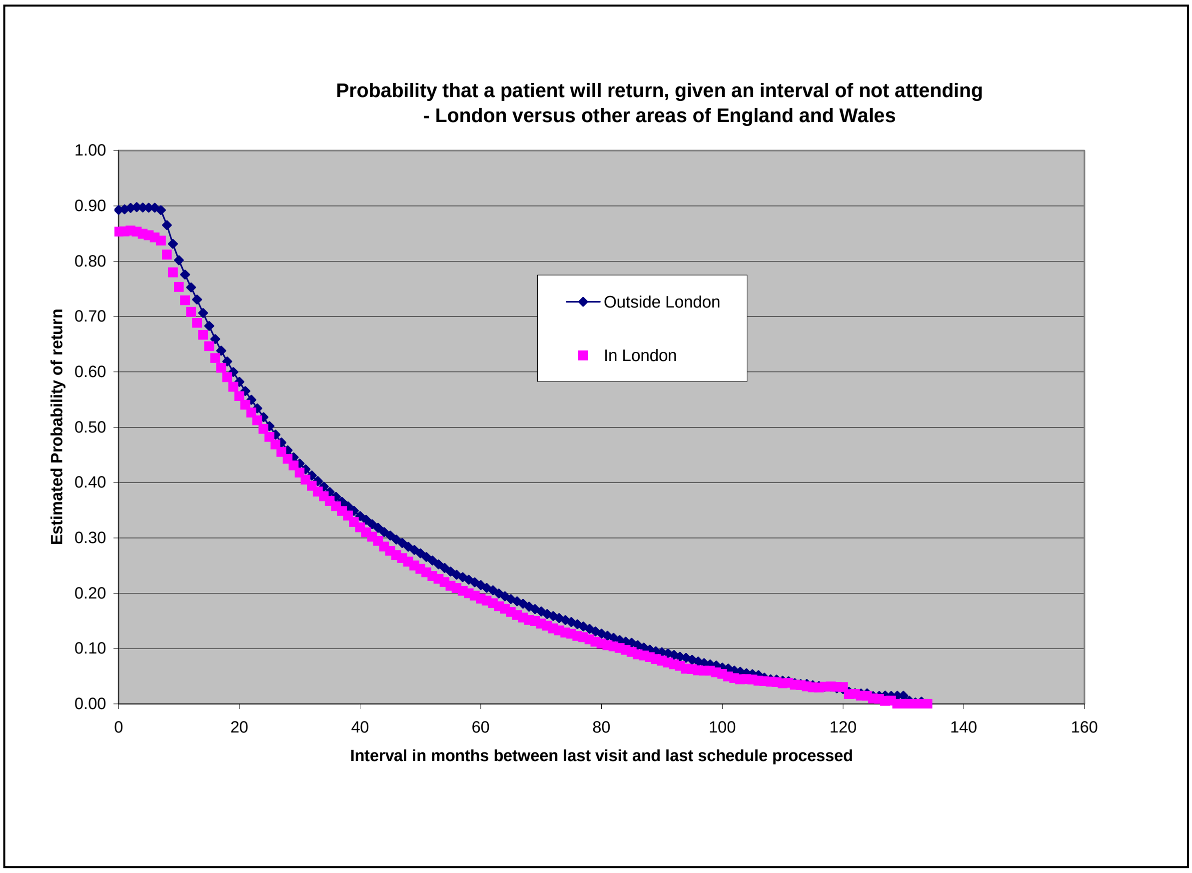


In order to demonstrate that the follow-up period for this study was sufficient to use the eleven-year estimation of probability of non-return as though it applied absolutely the proportion of non-returning patients was plotted against the number of years of follow-up. For example, there were 75,335 courses of treatment with the last recorded date in 1997, of which 6,734 (0.089) had no further courses for the same patient recorded before the March 2002 payment schedule – a follow-up period of five years. As the chart (Figure 4.13) shows, after the first five years or so of follow-up, the proportion of the original cases who re-attended flattened out at approximately 0.08. The slight increase as the years of follow-up increase may be attributable to poorer data quality at the start of the observation period (1991), when dentists were coping with new claim forms and coding requirements introduced with the then ‘New Dental Contract’ in October 1990.

It is of course still logically possible that patients could return in large numbers after an interval of over ten years, but the above analysis indicates that this would constitute a change from a smooth pattern established over the period which has actually been observed.

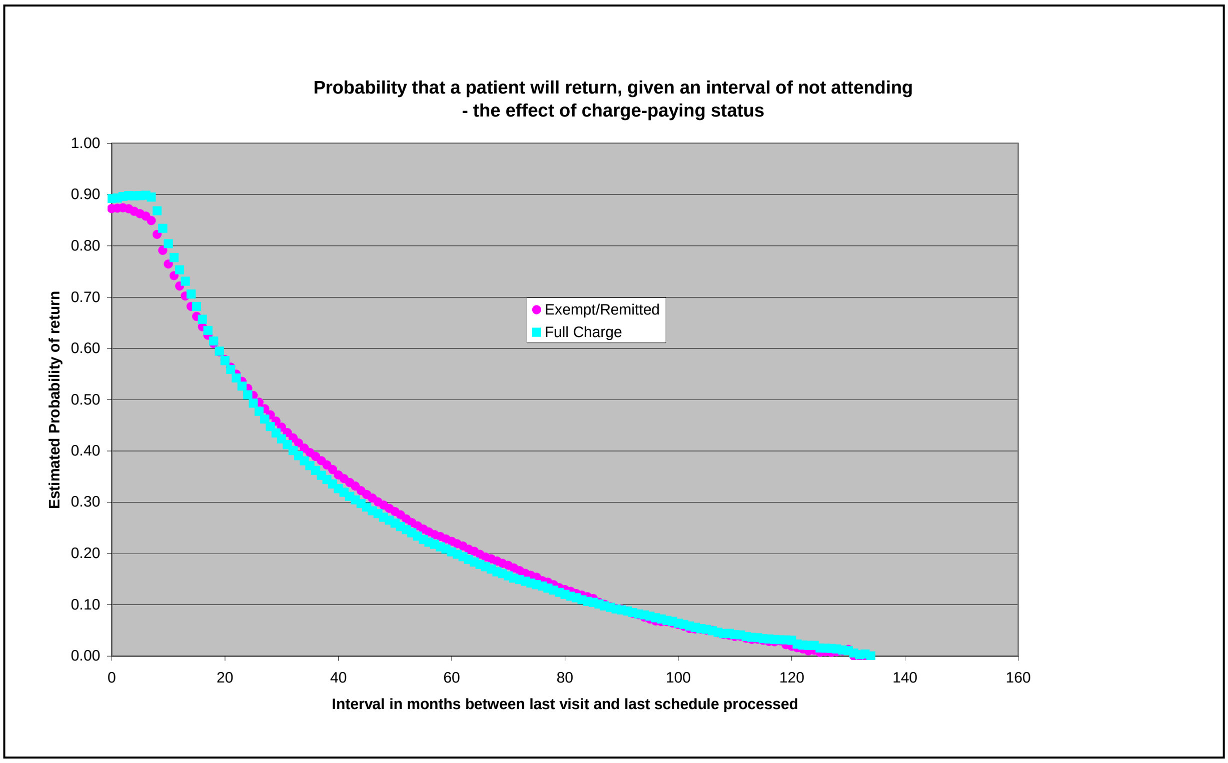
Consider now the relative likelihood of re-attendance of London patients compared with those elsewhere. It is known that London patients attend less frequently, but it does not follow that the conditional probability of re-attendance, given a period of non-attendance, will be different for all such periods. The chart (Figure 4.14) shows the comparison between the two types of patient. It can be seen that, although the initial probability of re-attendance for London patients was indeed lower than that for patients elsewhere, after the initial six months there was very little difference between the two curves. Although, given the volume of data, the difference may be statistically significant, it was clearly small. Since the minimum censor time chosen for censoring cases was 365 days after last visit (section 3.4.3), the different probabilities of eventual re-attendance in the first year after the end of a course of treatment will have no effect on the resulting estimate of the cumulative survival function.

Figure 4.14 Probability of patient re-attendance – London



Now consider charge-paying status (Figure 4.15). Again, the overall frequency of attendance is known to be greater for charge-payers than for patients with exemption or remission.

Figure 4.15 Probability of patient re-attendance – charge-paying status



Once again, although the initial probability of return is greater for charge-payers, after the first six months the two curves become virtually indistinguishable. A possible explanation for both these patterns is that a greater proportion of London patients, and a greater proportion of patients with exemption or remission, attend at longer intervals than every six months, but that in other respects they are as likely to re-attend, eventually, as any other patient.

Figure 4.16 shows that there was a difference between males and females in their likelihood of re-attending after a given interval, but that the difference was relatively small. In section 4.3.3.5 it is shown that the inclusion of an adjustment for this difference has a negligible effect on the resultant empirical survival curve.

Figure 4.16 Probability of re-attendance – patient sex

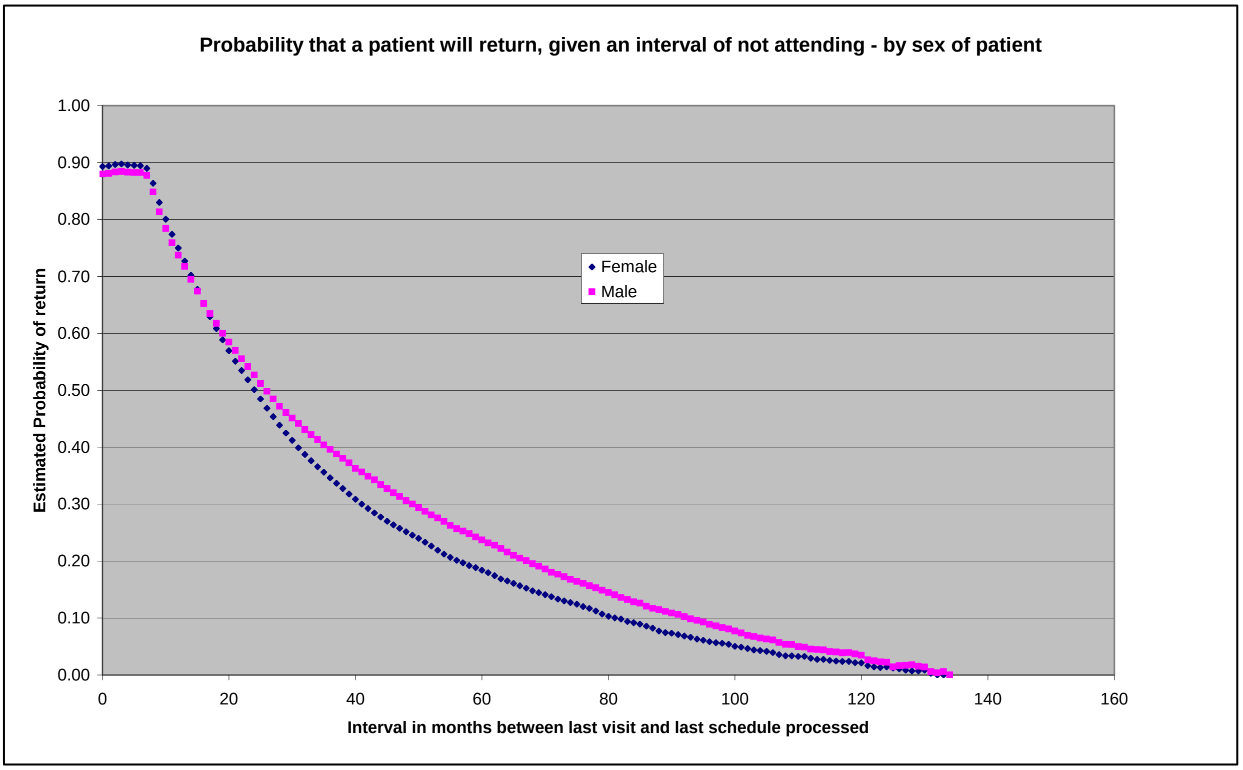
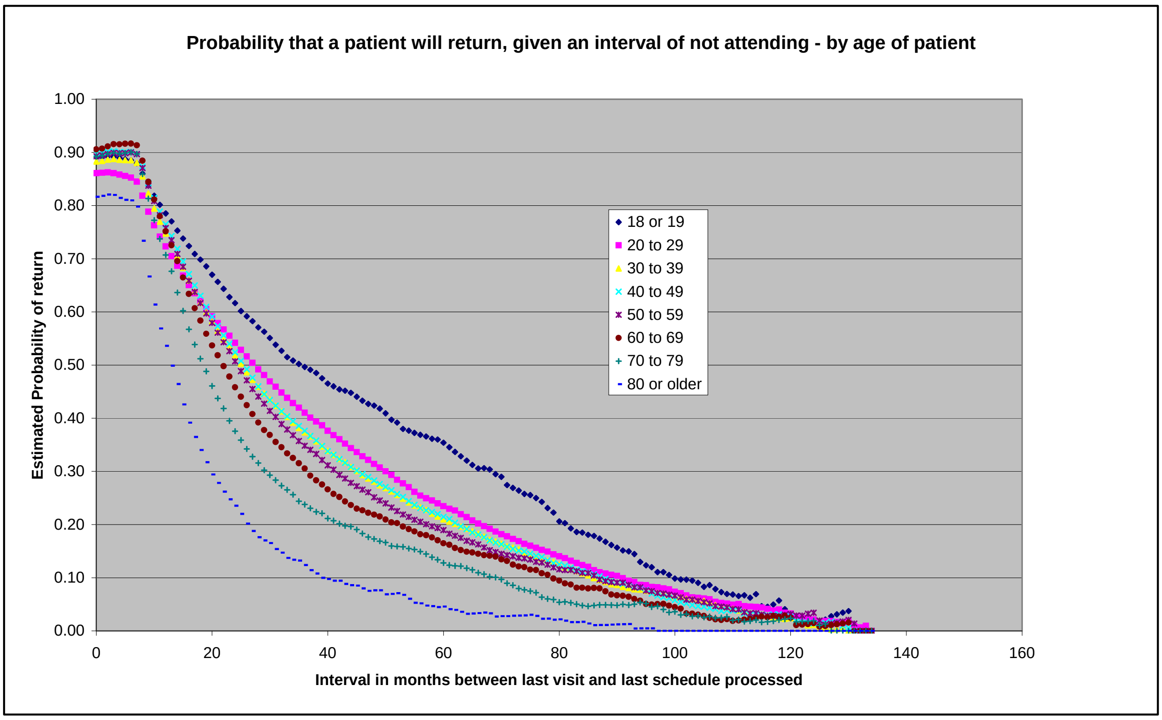


Figure 4.17 Probability of re-attendance – patient age



Patient age is another factor which might be expected to be associated with differing re-attendance probability. Younger patients are less settled in their domicile or attendance patterns, and so are more likely to have long gaps between visits. At the other end of the age spectrum, the probability of re-attendance may be influenced by the literal life expectancy of the patients. A patient over the age of 80 at last visit who has not subsequently attended in ten years may no longer be alive. Figure 4.17 shows that there was indeed a difference between patients of different ages in their conditional probability of eventual return after a given interval of non-attendance. Outside the extremes of age however, the differences are reasonably small.

Whatever the full explanations, these analyses have shown that the empirical relationship between follow-up time and likelihood of re-attendance is robust, varying little even across subgroups which are known to have different attendance patterns. Nevertheless, the variation with age was considered sufficiently important to justify stratifying the analysis by age group of patient. A further refinement of this method could be to model the likely eventual re-attendance function, G(m), by a logistic regression on appropriate independent variables, at least for m>12, where m is the interval in months between last visit and last schedule processed.

It can be seen from Figure 4.18 that assuming censoring only at the end of the observation period becomes progressively more unrealistic, as non-returners gradually accumulate. However, all four methods give very similar results for the first year. The criticism of the increasing accumulation of non-returners also applies to the ‘half-way’ option.

Figure 4.18 Sensitivity to alternative censoring assumptions

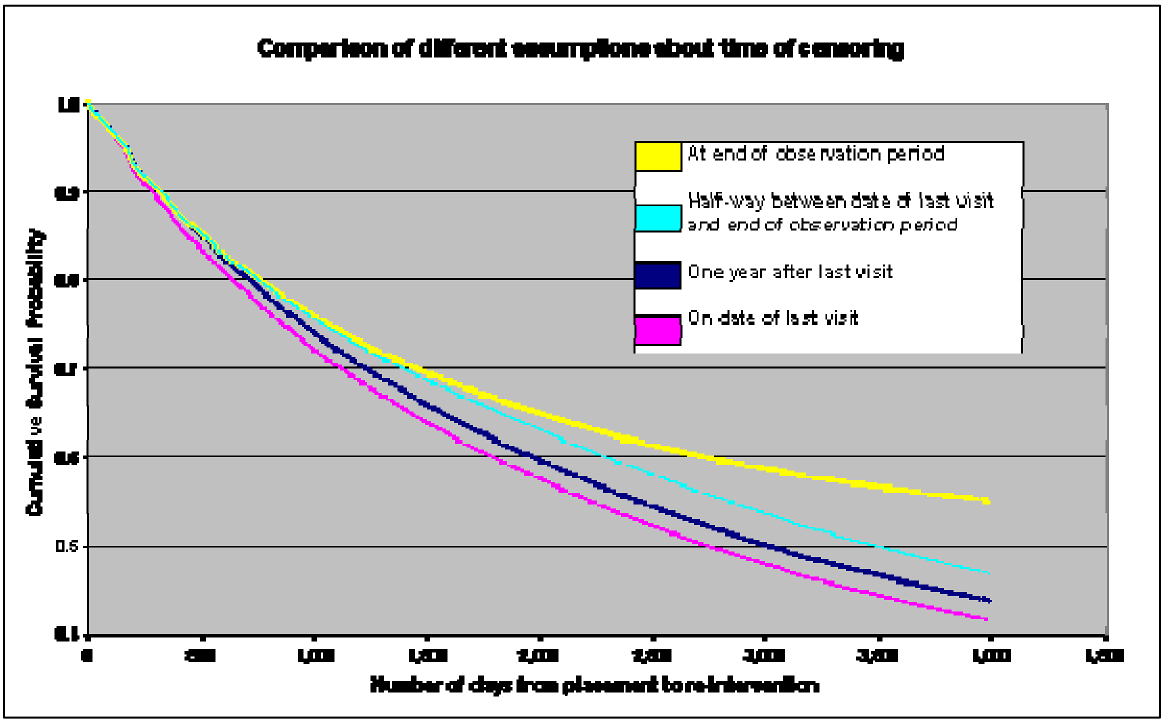


Figure 4.18 shows the results of applying the four different censor time assumptions suggested in section 3.4.3. Assuming immediate loss from the ‘at risk’ population gives the lowest cumulative survival curve, but this assumption is unrealistic. The normal check-up interval in the GDS is six months. Only after this period has expired would a patient normally expect to go to another dentist, unless there are special circumstances such the departure of the previous dentist or a breakdown of trust. Two other considerations suggest that a period of around a year may be appropriate as an interval before censoring. The first is the GDS ‘guarantee’ period, whereby the NHS undertakes to pay for the replacement of any restoration which fails within twelve months. The second is the re-registration interval – the time after a visit for which, without other action, a registered patient may expect to receive the benefits of being a registered patient, including urgent treatment within 24 hours. In 1991 this period was two years. In September 1996 the period was reduced to fifteen months, plus the remaining days in the month of re-registration. The chart (Figure 4.18) demonstrates that increasing the interval after the last visit to the effective date of censoring from zero to 365 days has only a modest impact on the survival curve, and comparisons between subgroups should be similarly affected, so the 365 day option has been adopted in all the standard analyses.

Finally, consider the methods of estimating standard errors developed in section 3.4.4. Applying these formulae to the data underlying the cumulative survival curve assuming censoring one year after last visit, as illustrated in Figure 4.12, the following results were obtained:

The 45th and 55th percentiles of the adjusted cumulative survivor curve are 3,761 and 2,429 days respectively.

Hence

$\hat{f}\{\hat{t}(50)\}$ = (0.55 – 0.45)/(3761 – 2429) = 0.1/1332

So $\frac{1}{\hat{f}\{\hat{t}(50)\}}$ = 13320

By definition of the fiftieth percentile $\hat{S}\{\hat{t}(50)\}$ = 0.5

so s.e. $\{\hat{S}\{t(50)\}\}$ ≈ $[\hat{S}\{t(50)\}]\{\sum_{j=1}^{k}\frac{d_j}{n_j(n_j - d_j)}\}^{\frac{1}{2}}$ =0.5 * $\{\sum_{j=1}^{k}\frac{d_j}{n_j(n_j - d_j)}\}^{\frac{1}{2}}$

and s.e.{$\hat{t}$ (50)} ≈ $\frac{1}{\hat{f}\{\hat{t}(50)\}}$ s.e.[$\{\hat{S}\{\hat{t}(50)\}$] = 13320 * 0.5 *$\{\sum_{j=1}^{k}\frac{d_j}{n_j(n_j - d_j)}\}^{\frac{1}{2}}$

At the 50th percentile, where t=3003,

$\{\sum_{j=1}^{k}\frac{d_j}{n_j(n_j - d_j)}\}^{\frac{1}{2}}$ = 0.0021436

So s.e.{$\hat{t}$ (50)} = 13320 * 0.5 * 0.0021436 = 14.28

The corresponding standard error calculated for the unadjusted survivor function is 11.51, which is of the right order, but too much lower to be acceptable.

Using significance probabilities and standard errors from SPSS analyses of unadjusted data is therefore unsatisfactory, since the effect of the larger sample size can be outweighed by the different values for the survival function and its gradient.

Accordingly, to obtain a better estimate of standard errors and significance levels, censoring has been applied randomly, according to the calculated estimate of the probability of return. Using SPSS on data of this form retains the correct sample size, and gives an unbiased, though variable, estimate of both the survivor function and the corresponding standard errors. Table 4.46 shows the resulting percentile points, and their standard errors, for the adjusted cumulative survivor function, the unadjusted, and two runs of the randomly censored estimate of the survivor function. It will be noted that SPSS has produced estimates of the standard error for the fiftieth percentile from the randomly censored survivor function which are consistent with that calculated directly for the adjusted survivor function.

It can be seen from Table 4.46 that the estimate derived from the unadjusted analysis is consistently less than the directly calculated value for the adjusted analysis, while the estimates based on the randomly adjusted analysis are much closer, and appear to be unbiased.

Table 4.46 Comparison of methods of estimation

	Time from treatment to re-intervention (days)				Standard Error			
Percentile	Unadjusted	Adjusted	Random 1	Random 2	Unadjusted	Adjusted*	Random 1	Random 2
95	168	168	168	168		0.96		
90	321	321	321	321	1.40	1.42	1.42	1.42
85	496	500	500	500	1.99	2.04	2.04	2.04
80	696	709	709	709	2.62	2.72	2.72	2.72
75	924	949	949	949	3.36	3.53	3.53	3.53
70	1,188	1,230	1,230	1,231	4.29	4.56	4.55	4.56
65	1,495	1,562	1,562	1,564	5.45	5.91	5.91	5.92
60	1,857	1,964	1,964	1,965	6.88	7.58	7.57	7.58
55	2,276	2,430	2,429	2,431	8.73	9.90	9.89	9.90
50	2,766	3,003	3,001	3,003	11.51	14.28	14.27	14.22
45	3,362	3,761	3,761	3,758				

* slope for 95th percentile based on ± 4 percentiles

Accordingly, in the analyses of survivor functions derived from the full longitudinal dataset, the adjusted methodology has generally been used to estimate the survivor function and its percentiles and other statistics of centrality and shape, while the random censoring methodology has been used to estimate the corresponding standard errors and to conduct significance tests.

4.3.3 Univariate Kaplan-Meier Analyses

This section describes the empirical findings for the variation of the interval between treatment and re-intervention according to various characteristics of the patient, the dentist, and the treatment. The estimates use the methodology described in section 3.4, including adjustment to take into account the age-related probability of eventual re-attendance by the patient. For the overall survival curve (4.3.3.2) the standard errors have been estimated using random censoring, for comparison with Table 4.46 in section 3.4.4. For the other tables the statistics have been presented in descriptive form only.

The overall survival analysis and the analysis by type of treatment are also illustrated by log cumulative hazard plots – a transformation of the cumulative survival curve. The shape of the cumulative hazard plot gives a clue as to the appropriateness of different underlying models (Collett, 1994). In particular a straight line could be expected from a Weibull underlying cumulative hazard function, and if the slope is close to unity, then an exponential function (a special case of the Weibull) is indicated. Furthermore, if the curves for different subgroups of the sample population are parallel then the underlying hazard functions are proportional to one another, in which case the Cox Proportional Hazard model is appropriate.

It should be remembered that these univariate curves reflect the inherent correlations between the various factors. For example, most amalgam restorations are placed in posterior teeth, and most restorations on incisors use composite resin as a restoration material. The finding that a particular subgroup of restorations has a greater or lesser median interval to re-intervention than another reflects all the attendant circumstances associated with that subgroup. There is no suggestion that the subgroups are composed of similar restorations, differing in only the factor by which the subgroups are defined.

The curves shown in this section (4.3.3) are not artificially smoothed – each point plotted represents an occasion when at least one restored tooth received re-intervention. The density of the points is therefore a useful reminder of the volume of data upon which each curve is based. The volume is indeed so great that any discernible kink in the curve or divergence between two curves is likely to be statistically significant. The reader can therefore safely concentrate on considering the clinical significance of such features of the curves. However, the appendix contains standard errors for all the quintiles on the curves, as well as the results of log-rank tests of differences between the curves for each of the factors.

4.3.3.1. Overall Survival Curve

Figure 4.19 presents the Kaplan-Meier survival curve across all the directly placed restorations included in this study. Most of the restorations include the restoration of the tooth surface by direct means, but there were also a number of root fillings which were accompanied by crowns or inlays (less than five per cent - numbers are given in Table 4.44). The curve is very smooth, with the exception of two small inflexions at around six and twelve months from the placing of the restoration.

Table 4.47 presents a set of summary statistics describing the curve. The median survival time was 3,004 days, or approximately eight years, with a standard error of 14 days. The ten year survival rate was 0.46 (46%) with a standard error of 0.0013 (0.13%).

Figure 4.19 Overall survival curve

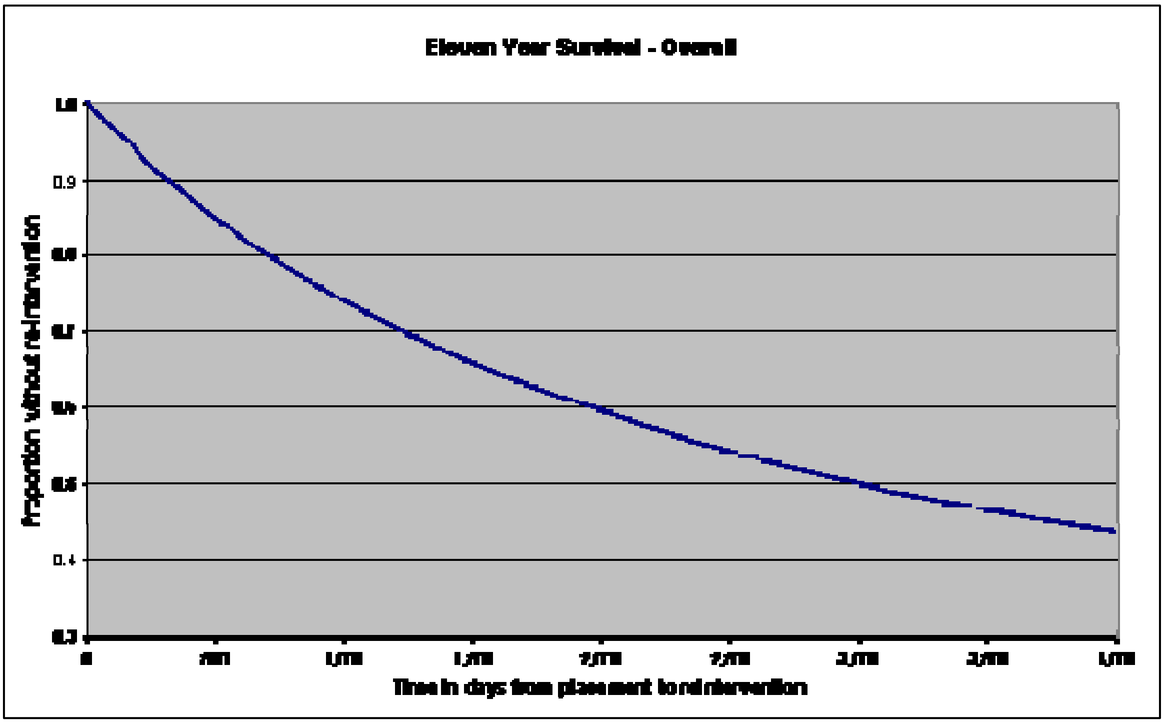


Table 4.47 Overall distribution statistics

Distributional Statistics - Overall			
Percentiles		Survival Rates	
Percentile	Survival Time (Days)	Elapsed time (Years)	Percentage Surviving without re-intervention
95	168	**1**	**89%**
90	321	2	79%
85	500	3	72%
80	709	4	66%
75 (Upper Quartile)	**949**	**5**	**62%**
70	1,231	6	57%
65	1,563	7	54%
60	1,965	8	51%
55	2,432	9	48%
50 (Median)	**3,004**	**10**	**46%**

Figure 4.20 Log cumulative hazard plot for whole dataset

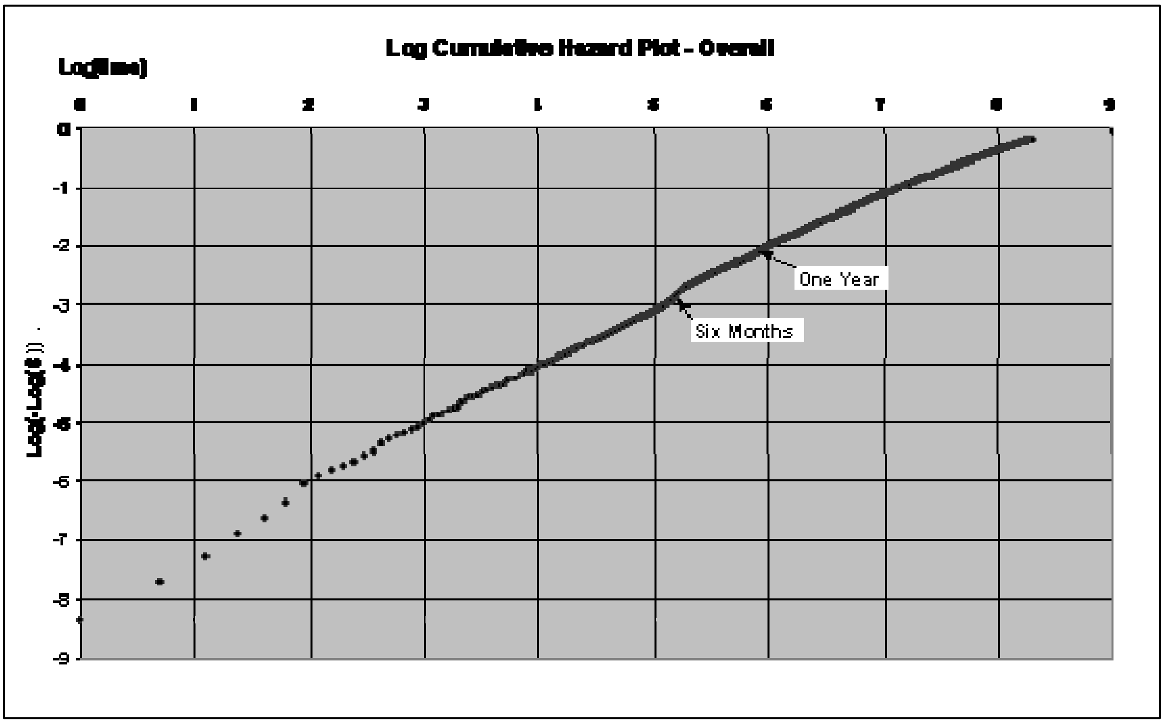


Figure 4.20 gives the log cumulative hazard plot for the overall curve. It will be noted that the two inflexions correspond to those on the cumulative survival curve (Figure 4.19). Apart from that, the cumulative hazard plot approximates to linearity, with a slope close to unity.

4.3.3.2. Treatment Type

Figure 4.21 compares the survival curves for different types of restoration, derived from their SDR treatment codes. With the exception of tunnel restorations and root fillings with indirect restorations the curves spread out uniformly across the whole of the observation period. Single surface amalgam restorations survived best and glass ionomers worst.

Figure 4.21 Cumulative survival by treatment type

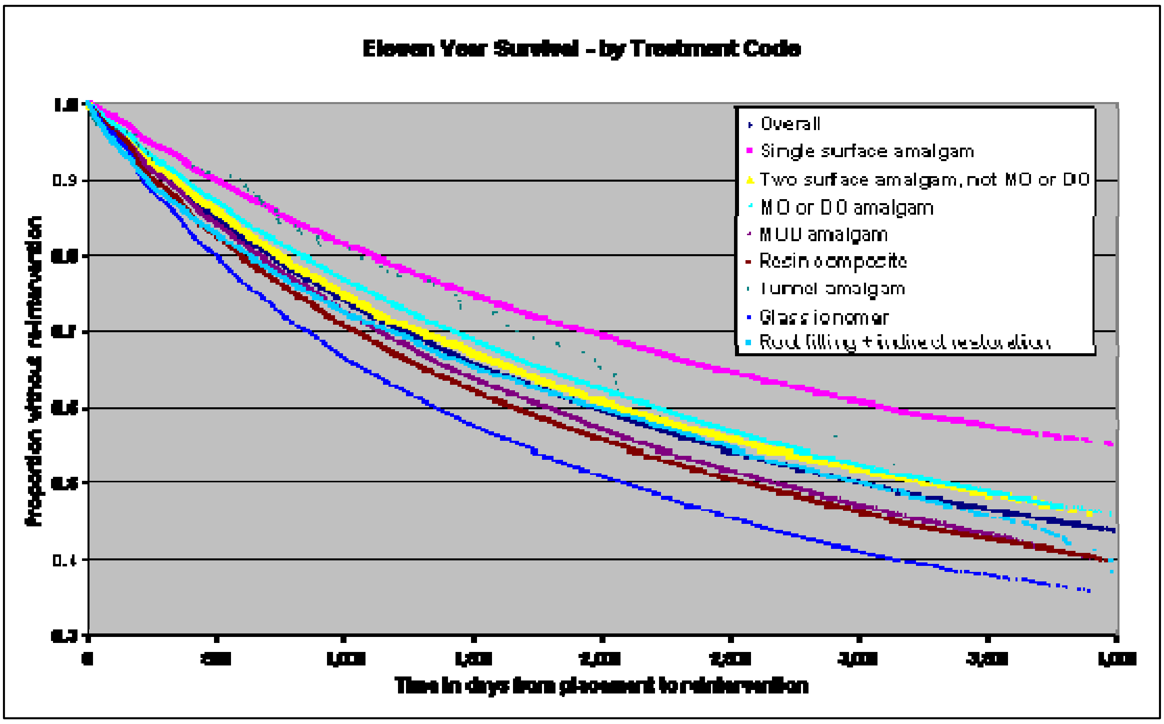
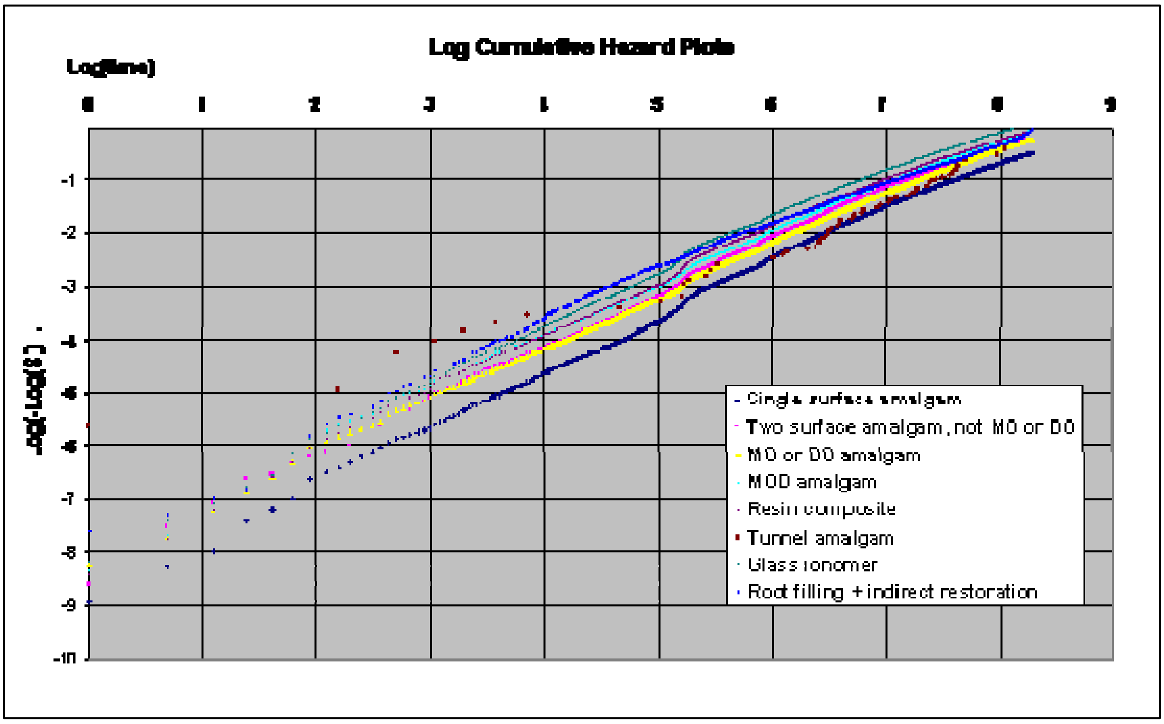


Table 4.48 Distribution statistics for different types of restoration

	Percentiles		Survival Rates		
Treatment Type	Upper Quartile	Median	I year	5 Year	10 Year
Single surface amalgam	1,479	N/A	0.93	0.71	0.57
Two surface amalgam, not MO or DO	995	3,288	0.89	0.63	0.48
MO or DO amalgam	1,100	3,306	0.90	0.64	0.48
MOD amalgam	885	2,656	0.88	0.59	0.42
Resin composite	803	2,541	0.87	0.58	0.42
Tunnel amalgam	1,429	N/A	0.93	0.68	0.53
Glass ionomer	652	2,070	0.84	0.53	0.37
Root filling + indirect restoration	859	2,993	0.86	0.62	0.45

Table 4.48 provides summary distribution statistics and Figure 4.22 the log cumulative hazard plots for the different treatment types. These confirm that tunnel restorations and root fillings with indirect restorations were exceptional, and that the other types of restoration showed the same shape as the overall log cumulative hazard, and furthermore, they appeared to be very nearly parallel.

Figure 4.22 Log cumulative hazard plots for different types of restoration



4.3.3.3. Tooth Position

Tooth position is closely associated with the choice of restoration material.

Figure 4.23 shows the survival curves for the eight different tooth positions. Survival to next intervention was best for restored third molar teeth (position 8) and poorest on anterior teeth (positions 1, 2 and 3). Though statistically significant, the differences between different mouth quadrants were too small to be of clinical significance (Figure 4.24). Table 4.49 and Table 4.50 give the appropriate survival statistics. Where N/A is given for the median this indicates that over the period of observation the median had not yet been reached.

Table 4.49 Survival by tooth position

	Percentiles (days)		Survival Rates		
Tooth Position	Upper Quartile	Median	I year	5 Year	10 Year
1	720	2,286	85%	56%	39%
2	779	2,437	86%	57%	40%
3	792	2,394	87%	56%	40%
4	998	3,194	89%	63%	47%
5	985	3,123	89%	62%	46%
6	931	2,843	89%	61%	44%
7	1,096	3,471	90%	65%	49%
8	1,469	N/A	92%	71%	59%

Figure 4.23 Eleven year survival curves by tooth position

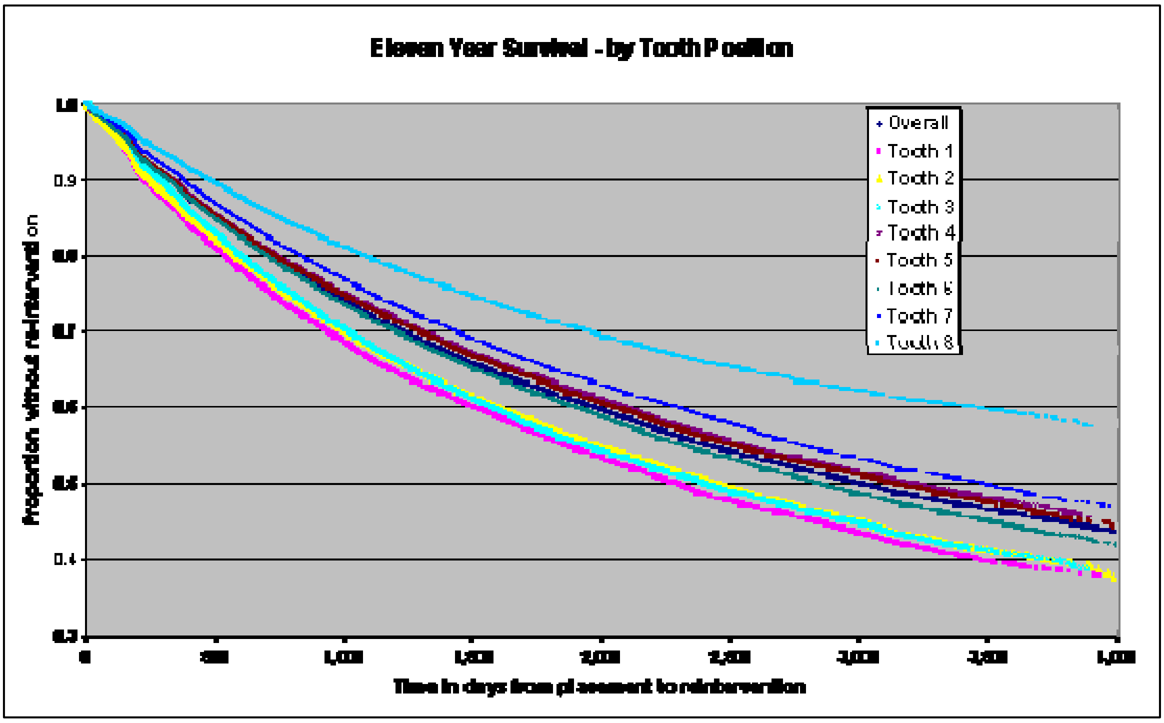
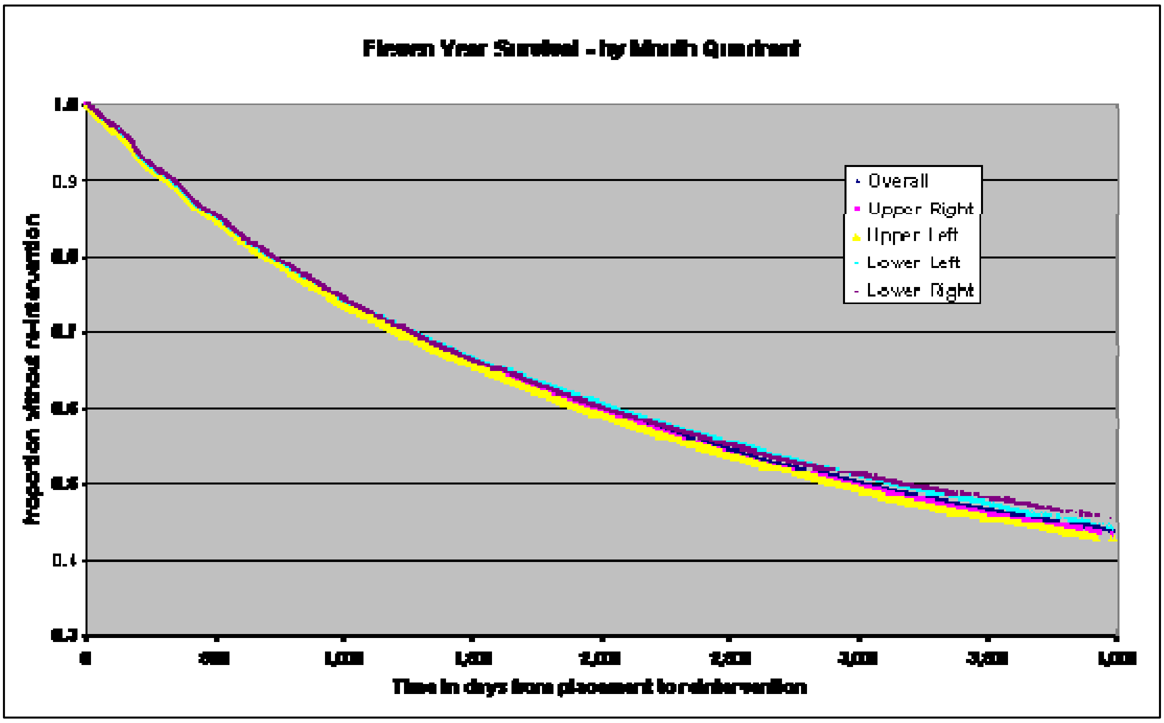


Table 4.50 Survival by mouth quadrant

	Percentiles		Survival Rates		
Quadrant	Upper Quartile	Median	I year	5 Year	10 Year
Upper Right	962	3,105	89%	61%	45%
Upper Left	966	3,146	89%	61%	45%
Lower Left	931	2,901	89%	62%	46%
Lower Right	945	2,938	89%	62%	47%

Figure 4.24 Eleven year survival by mouth quadrant



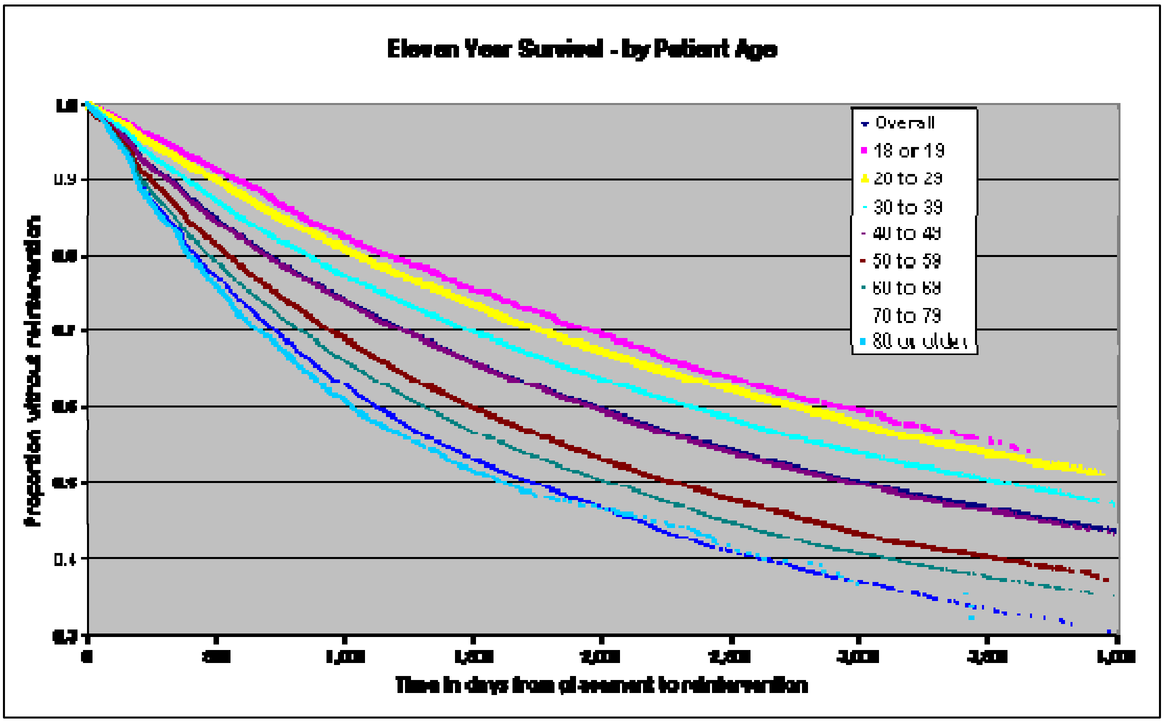
4.3.3.4. Patient Age and Other Characteristics

Patient age is clearly an important factor in the time from restoration to re-intervention, as can be seen from Table 4.51 and Figure 4.25. The older the patient, the shorter the interval to re-intervention. Where ‘N/A’ has been inserted for ten-year survival this indicates that no re-interventions were recorded at or after ten years. This applies in this table only to patients aged eighty and over at the date when the original restoration was placed.

Table 4.51 Survival by patient age

	Percentiles (days)		Survival Rates		
Patient Age	Upper Quartile	Median	I year	5 Year	10 Year
18-19	1,543	N/A	94%	71%	54%
20-29	1,395	N/A	93%	69%	53%
30-39	1,136	3,544	90%	66%	49%
40-49	934	2,953	88%	61%	45%
50-59	729	2,262	86%	55%	39%
60-69	630	2,024	84%	52%	37%
70-79	561	1,719	83%	49%	33%
80 and over	524	1,614	82%	48%	N/A

Figure 4.25 Eleven year survival by patient age



Patient sex however was of little significance in the long term survival of restorations, as can be seen from Table 4.52 and Figure 4.26. The short term lower survival of restorations in teeth of female patients noted from the early life analysis was not maintained throughout the longer term.

Table 4.52 Survival by patient sex

	Percentiles (days)		Survival Rates		
Sex of Patient	Upper Quartile	Median	I year	5 Year	10 Year
Female	940	3,051	88%	62%	46%
Male	957	2,955	89%	62%	45%

Figure 4.26 Eleven year survival by sex of patient

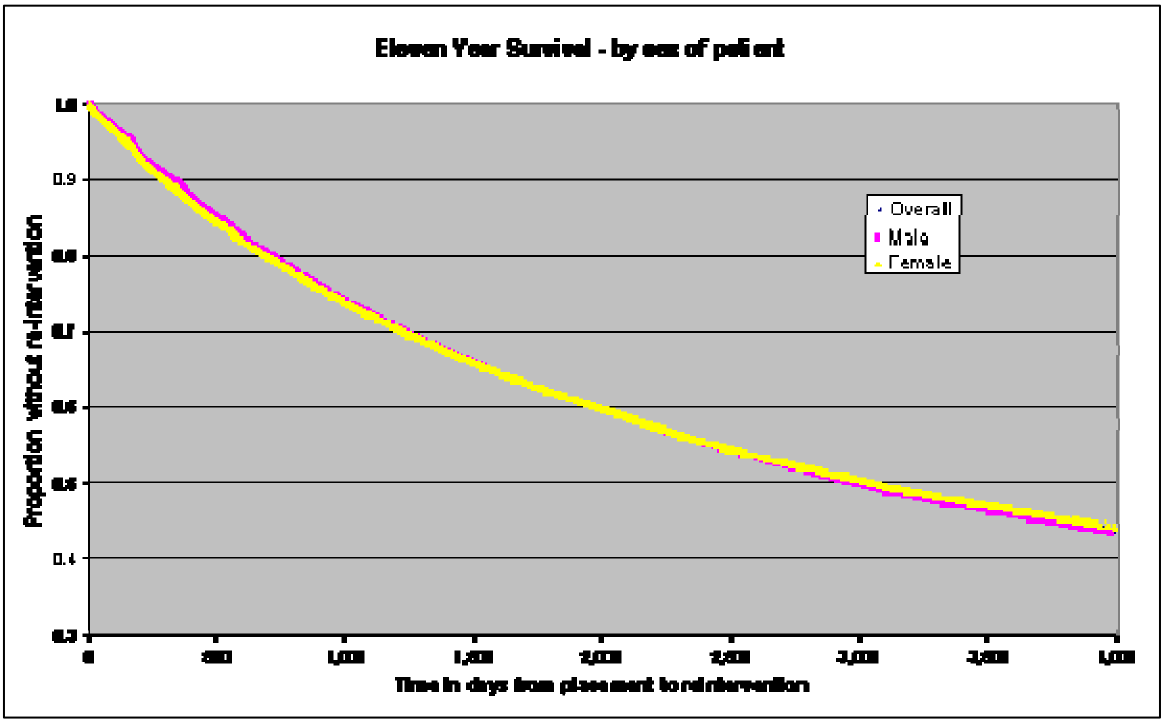
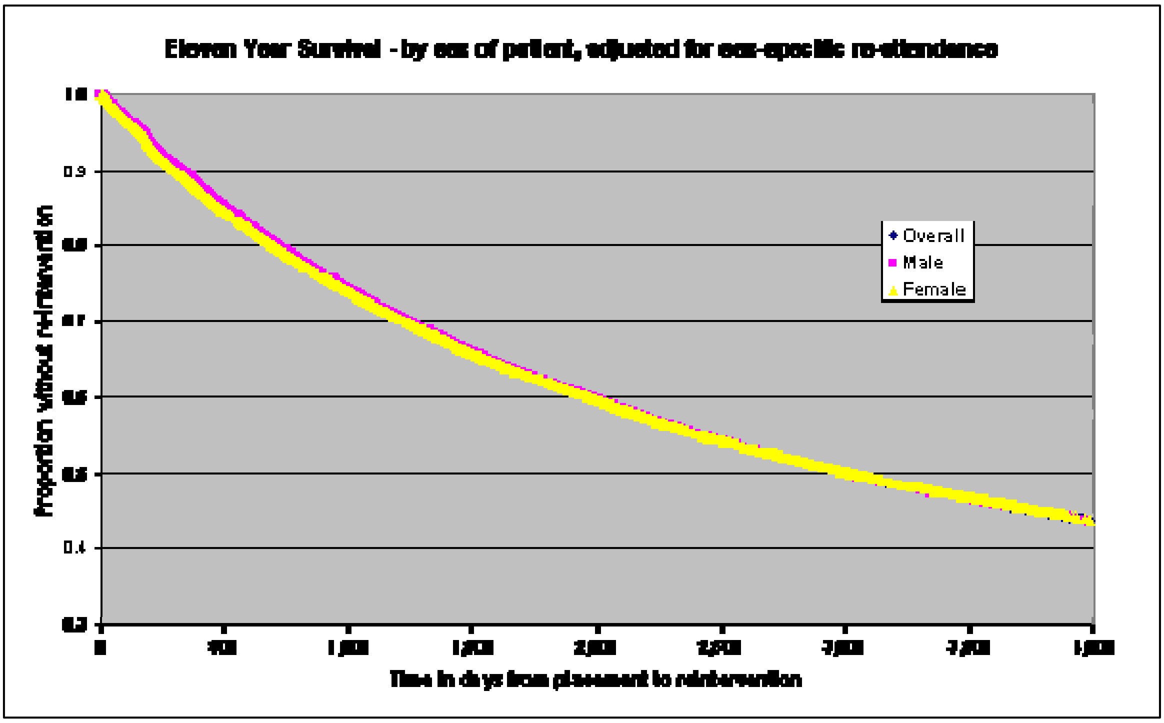


Figure 4.27 Adjusted eleven year survival by sex of patient



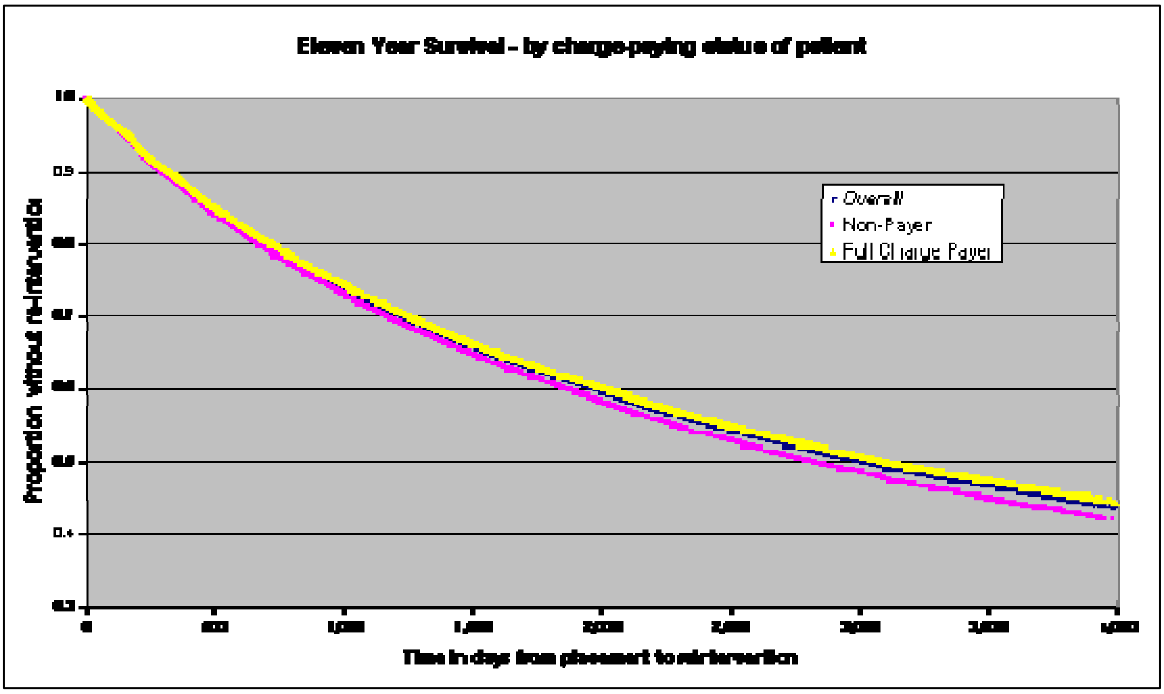
The exercise was repeated using adjustment for sex-specific probabilities of re-attendance (as described in section 4.3.2), but this made a negligible difference to the curves (Figure 4.27).

The charge-paying status of the patient had a statistically significant but small effect, with survival for charge-payers being slightly higher throughout the observation period (Table 4.53 and Figure 4.28).

Table 4.53 Survival by patient charge-paying status

	Percentiles (days)		Survival Rates		
Patient Charge-paying Status	Upper Quartile	Median	I year	5 Year	10 Year
Non-Paying	906	2,811	88%	60%	44%
Full Charge Payer	971	3,089	89%	62%	46%

Figure 4.28 Eleven year survival by charge-paying status of patient



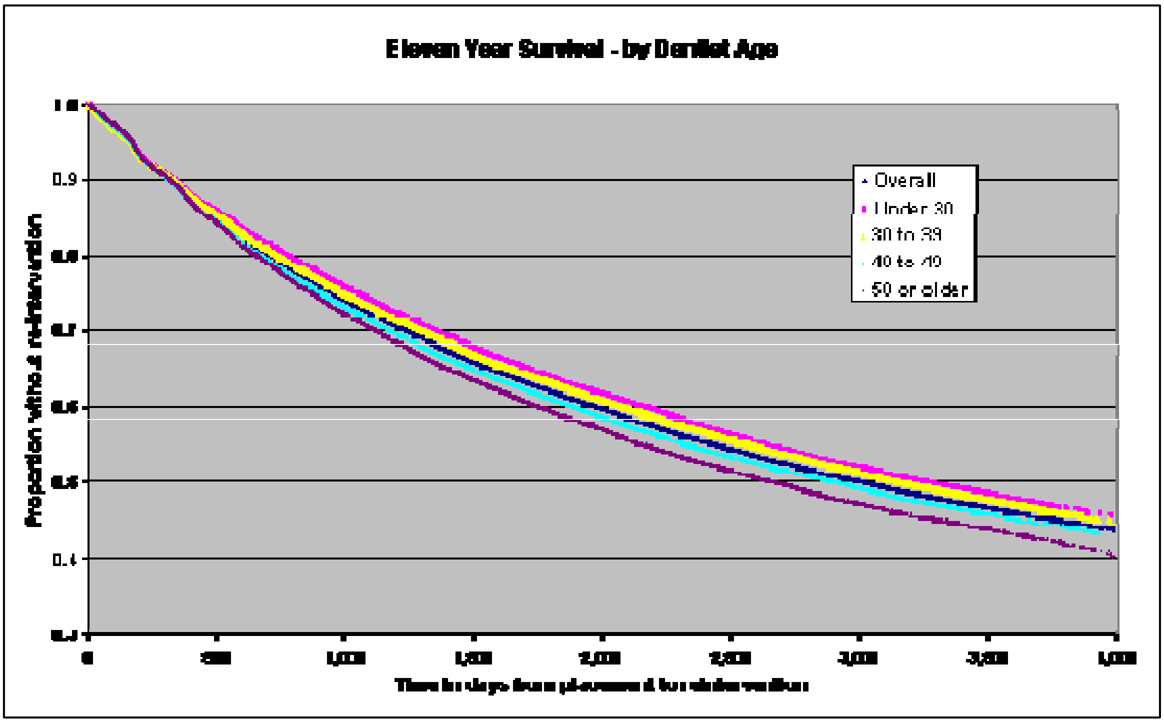
4.3.3.5. Dentist Characteristics

The age of the dentist placing the original restoration appears to be related to the interval to re-intervention, with older dentists having shorter intervals (Table 4.54 and Figure 4.29).

Table 4.54 Survival by age of dentist

	Percentiles (days)		Survival Rates		
Age of Dentist	Upper Quartile	Median	I year	5 Year	10 Year
Under 30	1,043	3,256	89%	63%	47%
30 to 39	993	3,146	89%	63%	47%
40 to 49	899	2,888	88%	60%	45%
50 or older	863	2,646	88%	59%	43%

Figure 4.29 Eleven year survival by age of dentist

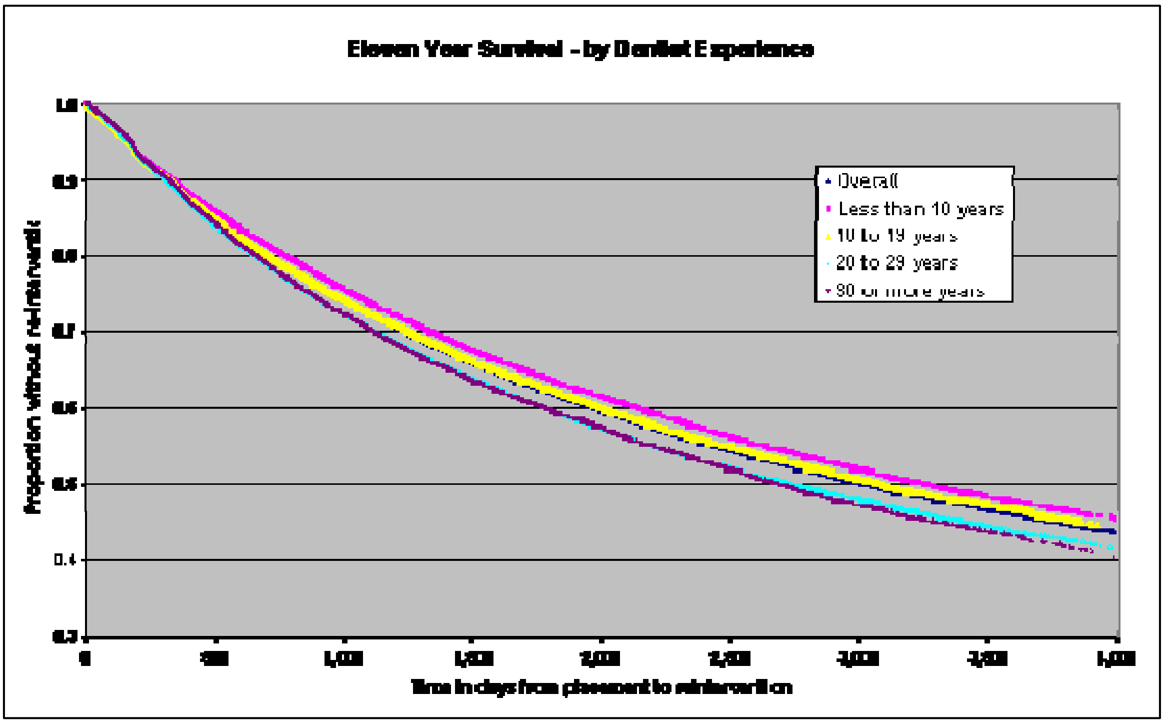


This is also reflected in the relationship between dentist experience, measured in years since qualification, and time to re-intervention (Table 4.55 and Figure 4.30).

Table 4.55 Survival by dentist experience

	Percentiles (days)		Survival Rates		
Dentist Years since qualification	Upper Quartile	Median	I year	5 Year	10 Year
Less than 10 years	1,030	3,238	89%	63%	47%
10 to 19 years	957	3,076	89%	62%	46%
20 to 29 years	864	2,722	88%	59%	43%
30 or more years	869	2,673	88%	59%	43%

Figure 4.30 Eleven year survival by dentist experience

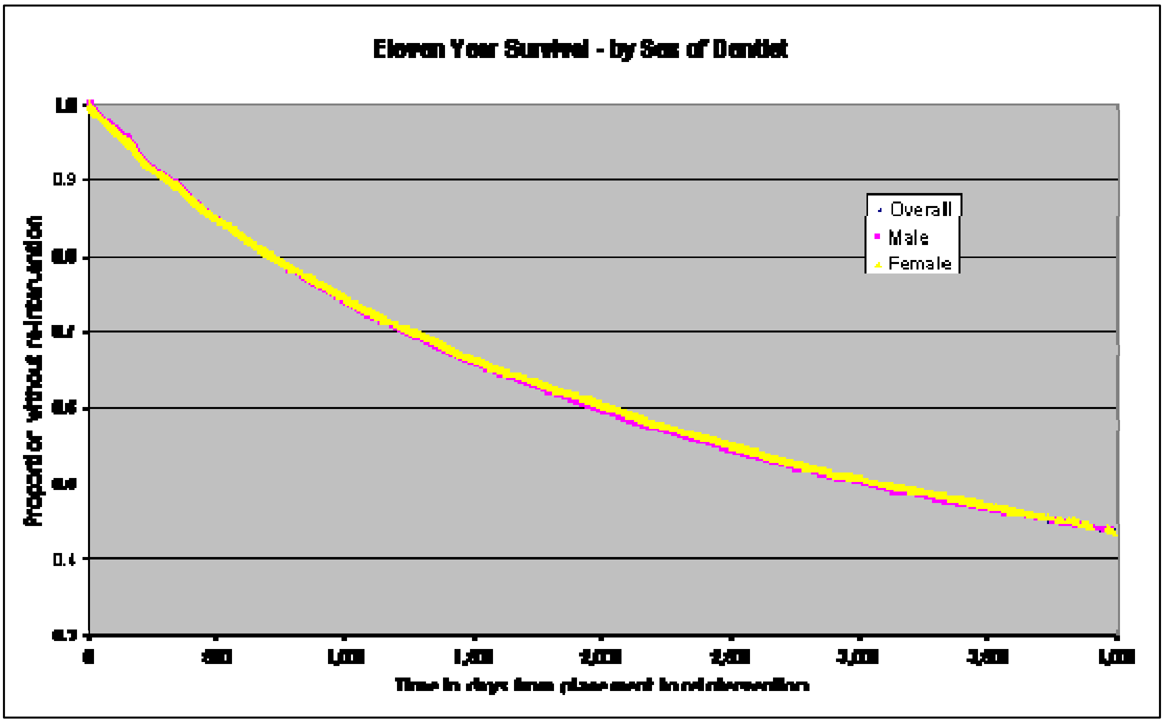


Dentist sex has no discernible relationship with time from restoration to re-intervention (Table 4.56 and Figure 4.31).

Table 4.56 Survival by sex of dentist

	Percentiles (days)		Survival Rates		
Sex of Dentist	Upper Quartile	Median	I year	5 Year	10 Year
Female	968	3,063	89%	61%	46%
Male	944	2,987	89%	62%	46%

Figure 4.31 Eleven year survival by sex of dentist

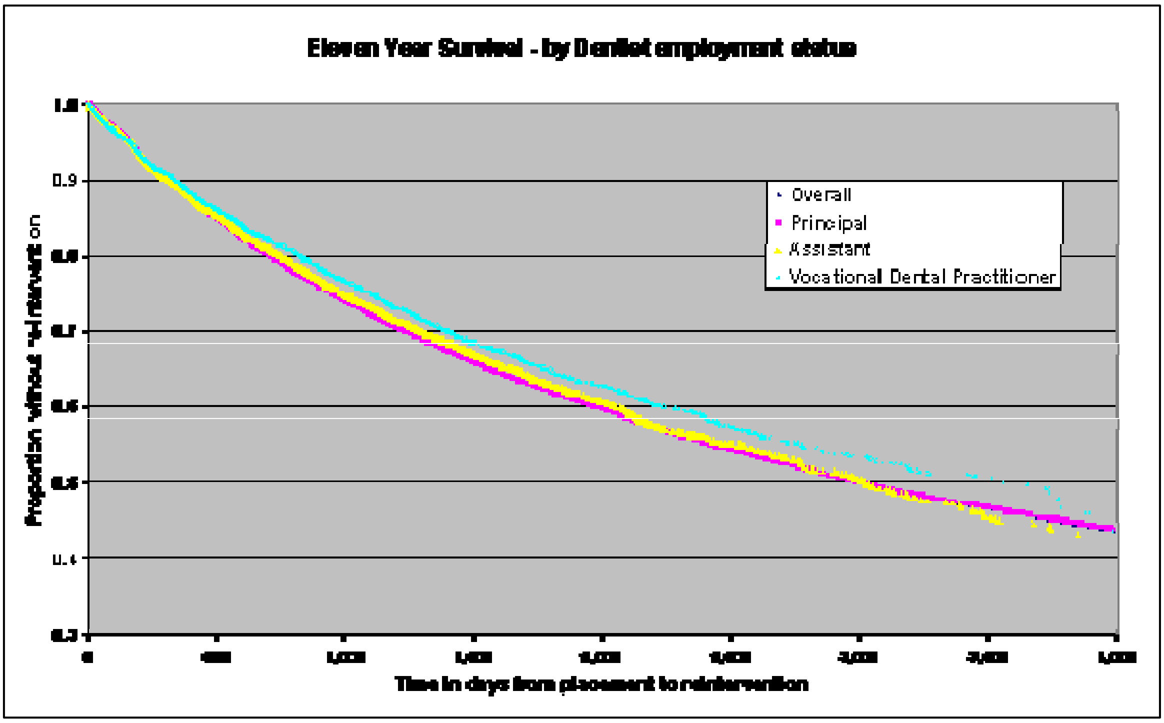


Dentist employment status gives further insight into the relationship between dentist age and experience and time to re-intervention, with the longest intervals recorded for vocational dental practitioners – generally young dentists in their first year since qualification (Table 4.57 and Figure 4.32). There were relatively few vocational dental practitioners (formerly known as vocational trainees) in the early part of the observation period.

Table 4.57 Survival by dentist employment status

	Percentiles (days)		Survival Rates		
Status of Dentist	Upper Quartile	Median	I year	5 Year	10 Year
Principal	945	2,996	89%	62%	46%
Assistant	991	3,025	89%	62%	45%
Vocational Dental Practitioner	1,093	3,562	89%	64%	50%

Figure 4.32 Eleven year survival by dentist employment status

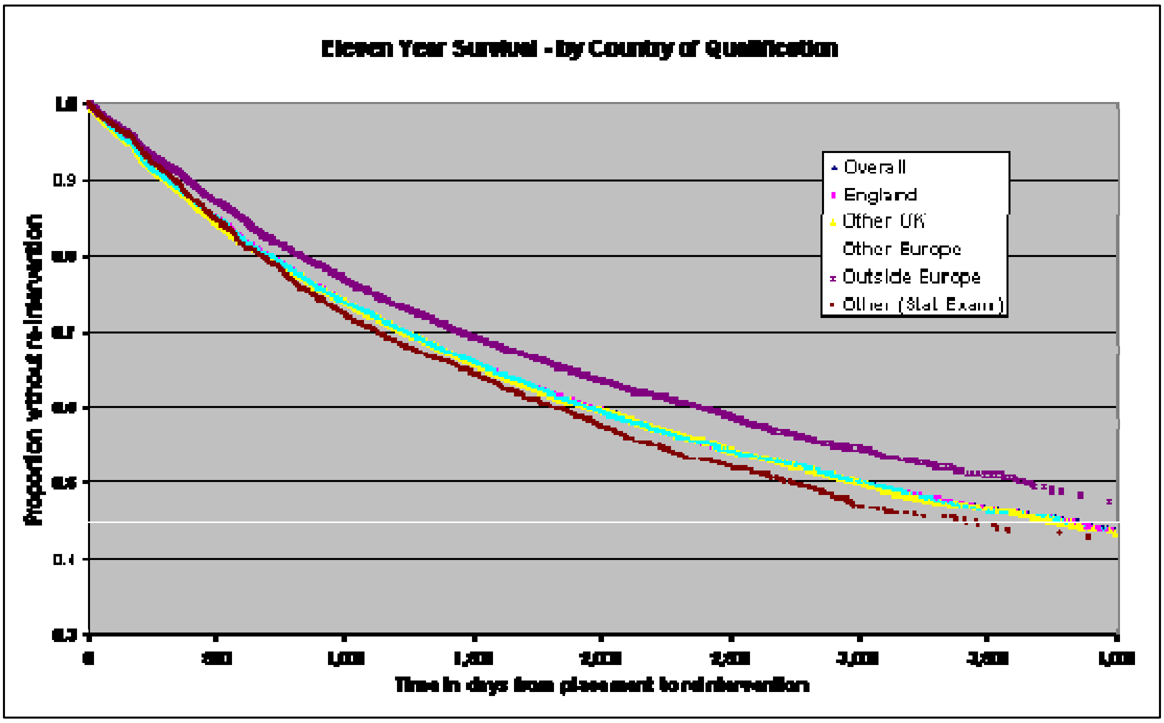


Country of qualification seems not to be relevant within Europe, but dentists qualified outside Europe appear to achieve different survival times. For those passing the statutory examination long term survival seems poorer, whereas those with other qualifications from outside Europe appear to achieve significantly better survival (Table 4.58 and Figure 4.33).

Table 4.58 Survival by dentist country of qualification

	Percentiles (days)		Survival Rates		
Dentist's Country of Qualification	Upper Quartile	Median	I year	5 Year	10 Year
England	942	2,977	89%	61%	45%
Other UK	943	2,995	88%	61%	45%
Other Europe	933	3,007	89%	61%	46%
Outside Europe	1,112	3,651	91%	65%	50%
Other (statutory exam)	878	2,735	89%	60%	44%

Figure 4.33 Eleven year survival by dentist country of qualification



4.3.3.6. Time and Place

Table 4.59 and Figure 4.34 show how survival varied with the year in which the restoration was placed.

Table 4.59 Survival by year of placement

	Percentiles (days)		Survival Rates		
Calendar year when restoration was placed	Upper Quartile	Median	I year	5 Year	10 Year
1991	1,045	3,123	91%	63%	47%
1992	1,048	3,186	90%	63%	48%
1993	1,001	3,088	89%	63%	N/A
1994	963	N/A	89%	62%	N/A
1995	960	N/A	89%	61%	N/A
1996	931	N/A	88%	61%	N/A
1997	908	N/A	88%	62%	N/A
1998	868	N/A	88%	N/A	N/A
1999	870	N/A	87%	N/A	N/A
2000	N/A	N/A	87%	N/A	N/A
2001	N/A	N/A	88%	N/A	N/A

The length of follow-up time was directly related to the year of placement, so that for example those restorations placed in the last four years had not been in place long enough to measure five-year survival. There was however some slight evidence of an overall reduction in survival times. One year survival reduced over the full observation period from 91% to 88%.

Figure 4.34 Eleven year survival by year of placement

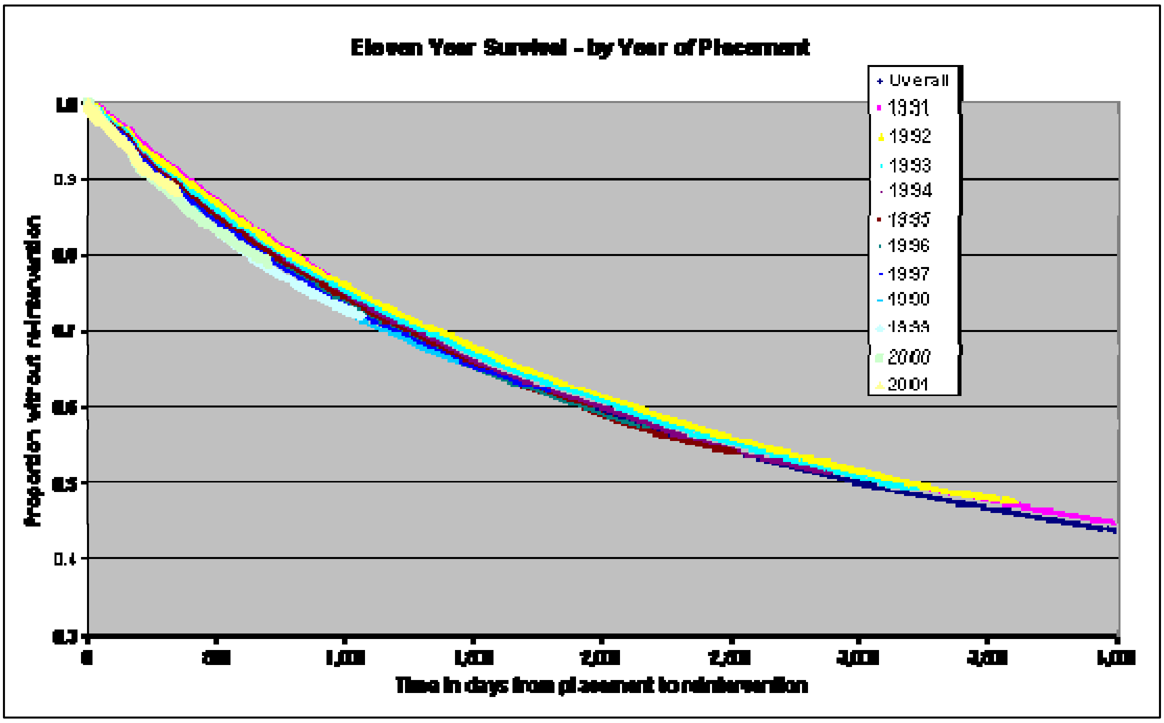


Table 4.60 and Figure 4.35 show the variation with month of placement. Although the variation was statistically significant, there did not appear to be any clinically significant seasonal variation.

Table 4.60 Survival by month of placement

	Percentiles (days)		Survival Rates		
Month when restoration was placed	Upper Quartile	Median	I year	5 Year	10 Year
January	908	2,910	89%	61%	45%
February	961	3,058	89%	62%	46%
March	953	3,001	89%	61%	46%
April	981	3,150	89%	62%	46%
May	972	2,954	89%	62%	45%
June	959	3,049	89%	62%	46%
July	970	2,980	89%	62%	45%
August	930	3,056	88%	61%	46%
September	913	2,899	88%	61%	45%
October	956	2,952	89%	62%	45%
November	967	3,078	89%	62%	46%
December	900	2,913	88%	60%	45%

Figure 4.35 Eleven year survival by month of placement

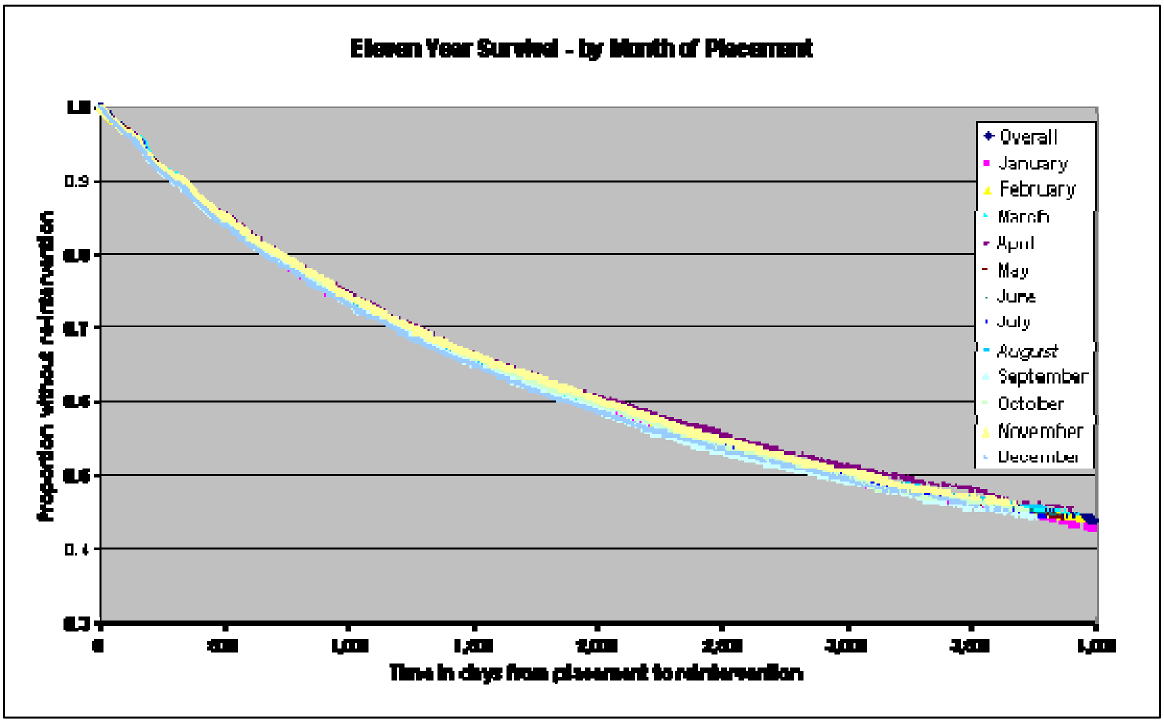


Table 4.61 and Figure 4.36 consider the region of the surgery, derived from the postcode. The variation with region is not great, but restorations placed in Wales survived till re-intervention significantly longer than those in England.

Table 4.61 Survival by region

	Percentiles (days)		Survival Rates		
Region	Upper Quartile	Median	I year	5 Year	10 Year
London	932	2,948	89%	61%	45%
South	923	2,993	88%	61%	46%
Central	967	3,085	89%	62%	46%
North	932	2,884	88%	61%	44%
Wales	1,034	3,128	89%	63%	47%

Figure 4.36 Eleven year survival by region

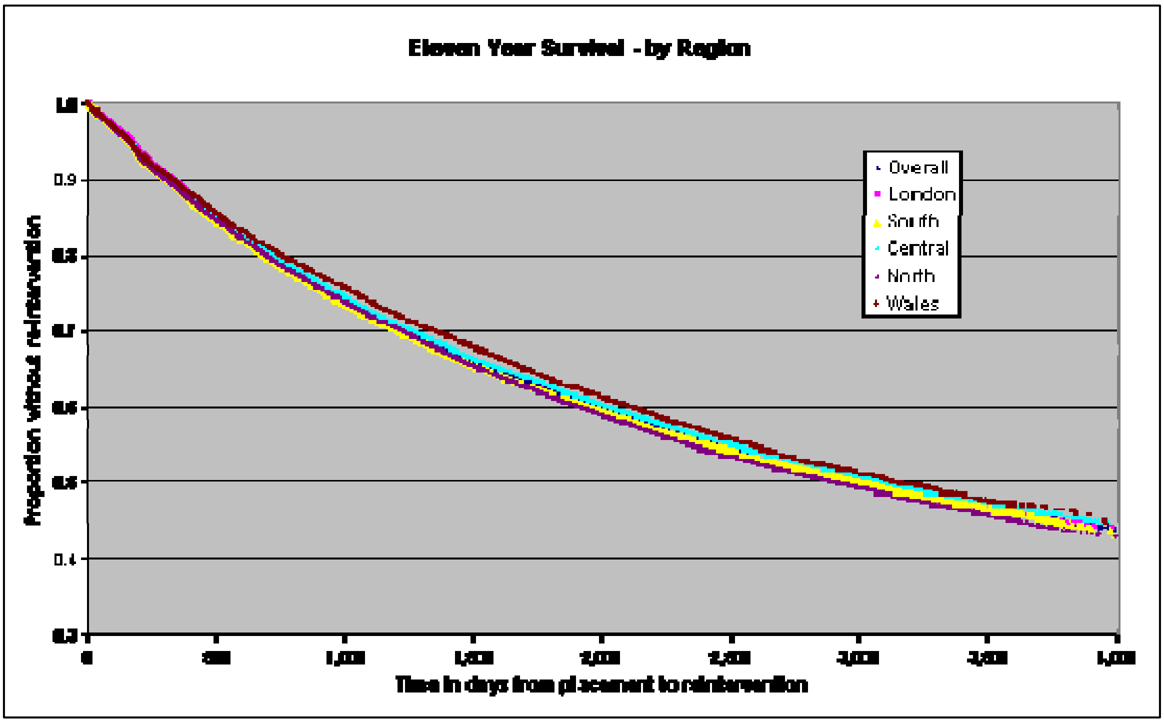


Figure 4.37 shows the source map on the basis of which surgery postcode areas were classified as fluoridated or not fluoridated.

Table 4.62 and Figure 4.38 indicate that there was no relationship between the presence or absence of fluoride and the survival times of restorations to re-intervention.

Figure 4.37 Fluoride concentrations in water supplies

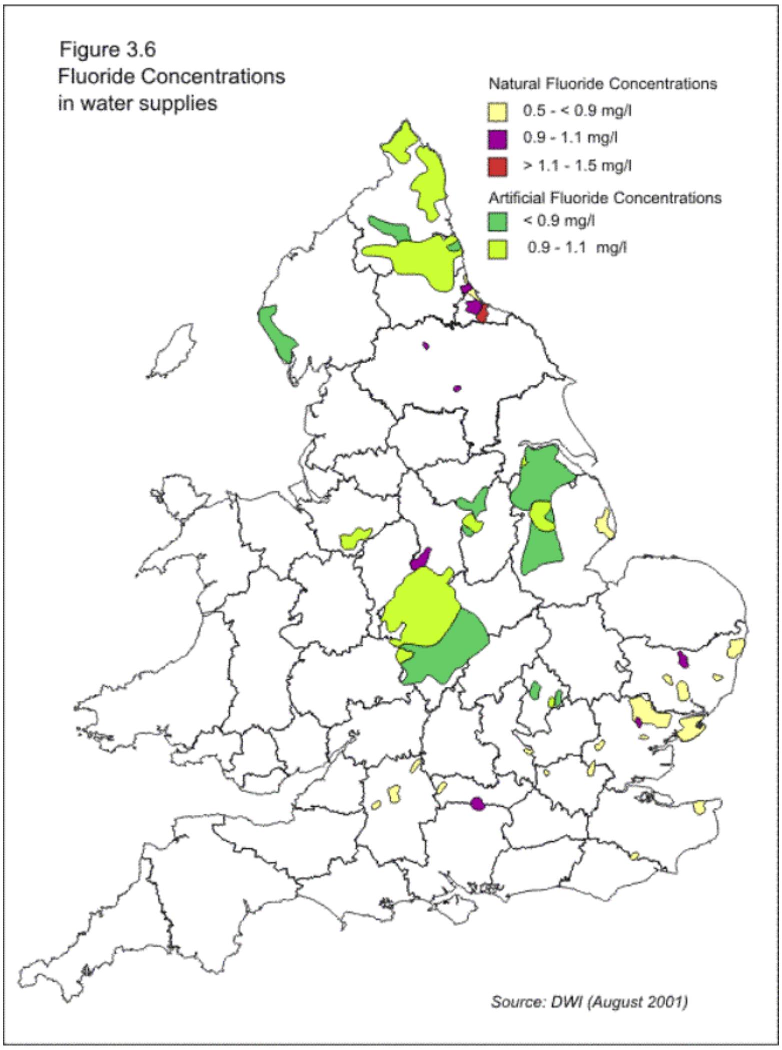
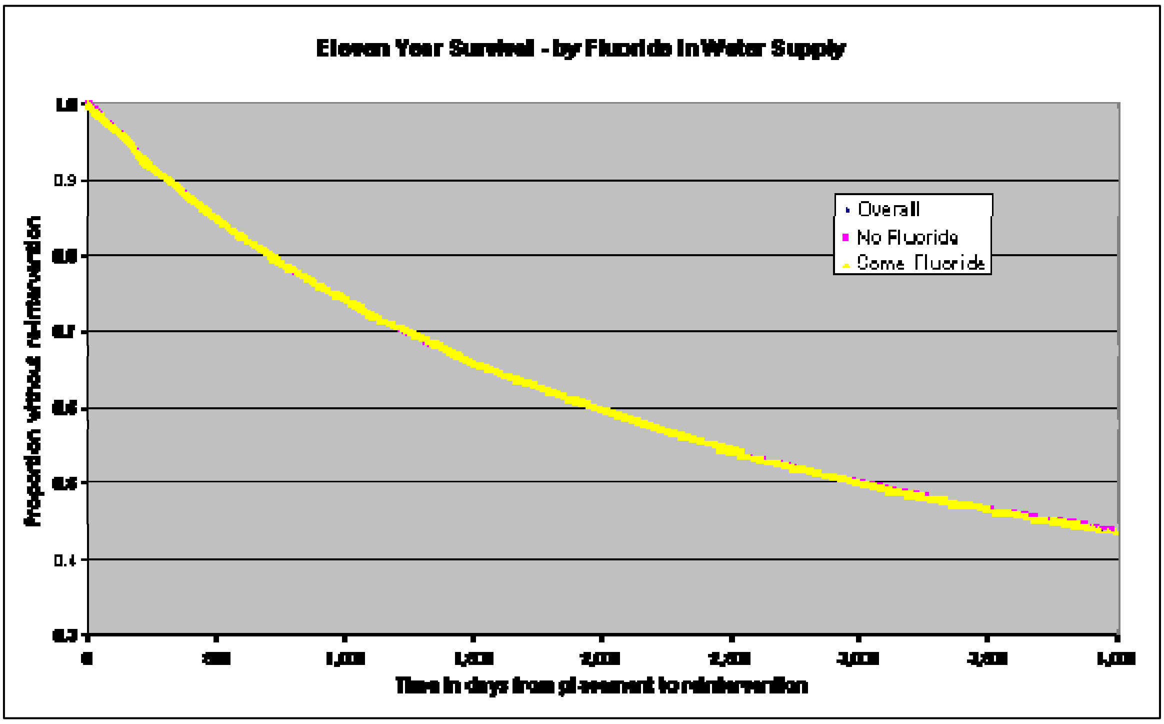


Table 4.62 Survival by fluoride presence

	Percentiles (days)		Survival Rates		
Presence of Fluoride in Water Supply	Upper Quartile	Median	I year	5 Year	10 Year
No Fluoride	945	3,010	89%	63%	47%
Some Fluoride	959	2,999	89%	62%	46%

Figure 4.38 Eleven year survival by fluoride presence



4.3.3.7. Patient Treatment History

Table 4.63 and Figure 4.39 show how survival varies with median attendance interval, taken over all courses of treatment experienced by the patient. Measurement of an interval in this case was calculated as the difference the dates of acceptance of two successive courses of treatment. Those patients who had only one course of treatment in the period of observation have been omitted from this analysis, since no interval can be computed. There is clearly a strong relationship between attendance frequency and survival time, but it should be remembered that the course in which the restoration was placed and that (if any) in which it received a re-intervention were included in the calculation. Where the total number of attendances was small (eg two attendances) then this relationship was definitionally reinforced.

Table 4.63 Survival by attendance interval

	Percentiles (days)		Survival Rates		
Median interval, for patients, between courses of treatment	Upper Quartile	Median	I year	5 Year	10 Year
under 150 days	445	1,453	78%	45%	29%
150 to 249 days	876	2,846	88%	60%	45%
250 to 399 days	1,251	3,775	92%	67%	51%
400 days or longer	1,953	N/A	97%	76%	58%

Figure 4.39 Eleven year survival by attendance interval

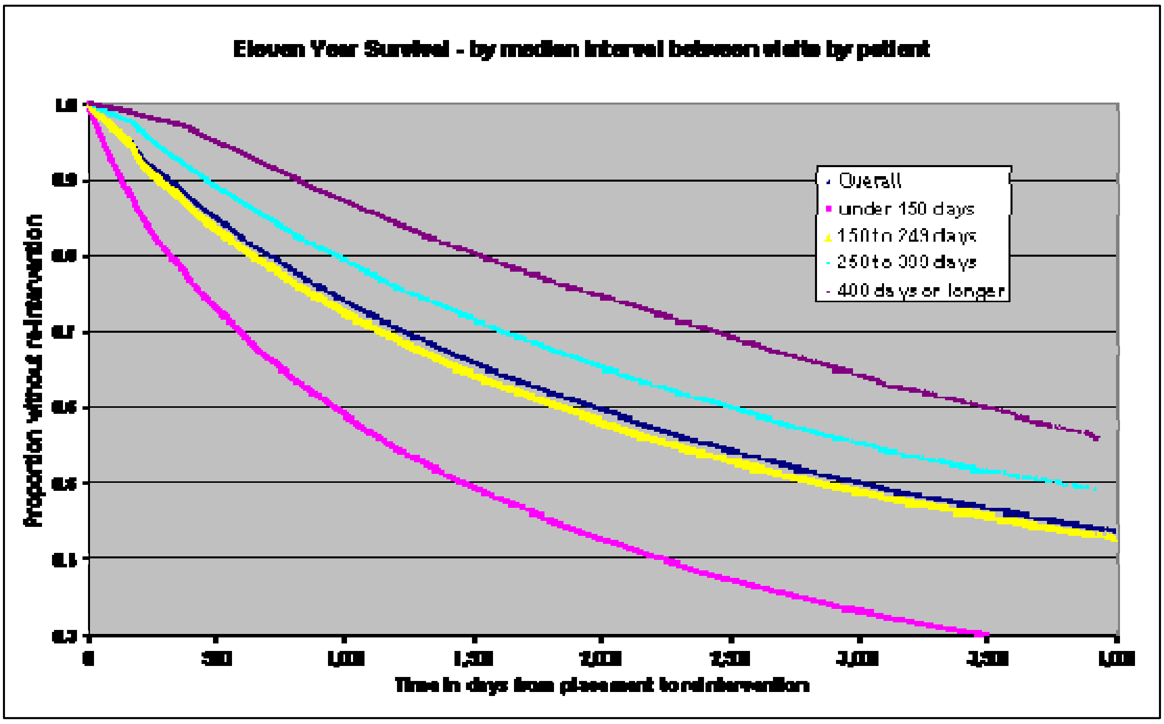


Table 4.64 and Figure 4.40 provide a similar analysis by the average annual cost for all the course of treatment received by the patient. This cost is the amount calculated according to the scale of fees in the Statement of Dental Remuneration current at the date of acceptance for the course of treatment, and includes any contribution levied from the patient in the form of a patient charge. The mean interval between courses was used to convert the total cost

into an annual figure, and again the analysis excludes those patients who had only one course of treatment.

Table 4.64 Survival by annual cost for patient

	Percentiles (days)		Survival Rates		
Mean annual scale fees for patient	Upper Quartile	Median	I year	5 Year	10 Year
Under £30	2,345	N/A	95%	79%	65%
£30 to £79.99	942	2,820	89%	61%	44%
£80 and more	532	1,493	81%	45%	28%

It can be seen that there is a big difference between restorations on patients with a high annual treatment cost and those with a low cost. There is less influence in this case between the number of courses of treatment and the shape of the curves, since the cost of a direct restoration is relatively modest, particularly where this is spread over an interval of a year or more.

Figure 4.40 Eleven year survival by mean annual cost for patient

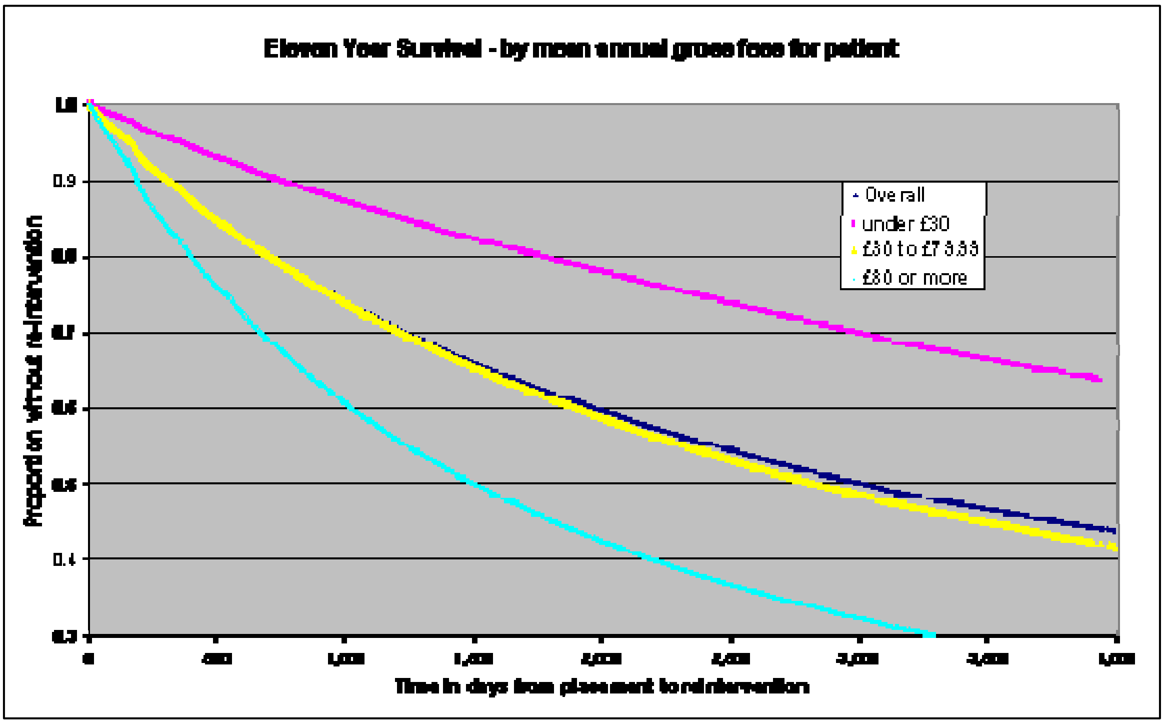


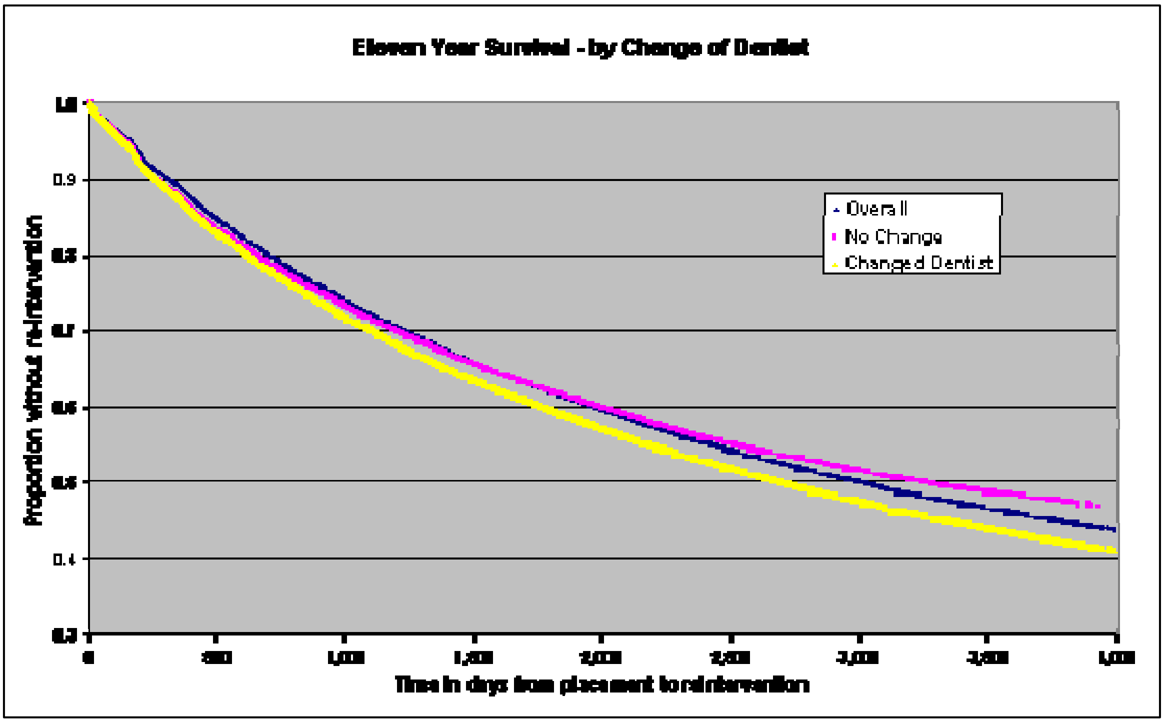
Table 4.65 and Figure 4.41 consider the attendance pattern of the patient after the restoration has been placed. Patients who had no further attendance after

that course of treatment have therefore been excluded from this analysis. It can be seen that a subsequent change of dentist is associated with an increased and increasing risk of re-intervention.

Table 4.65 Survival by subsequent change of dentist

	Percentiles (days)		Survival Rates		
Was there a subsequent change of dentist?	Upper Quartile	Median	I year	5 Year	10 Year
No Change	908	3,255	87%	62%	48%
Changed Dentist	847	2,697	87%	59%	43%

Figure 4.41 Eleven year survival by change of dentist

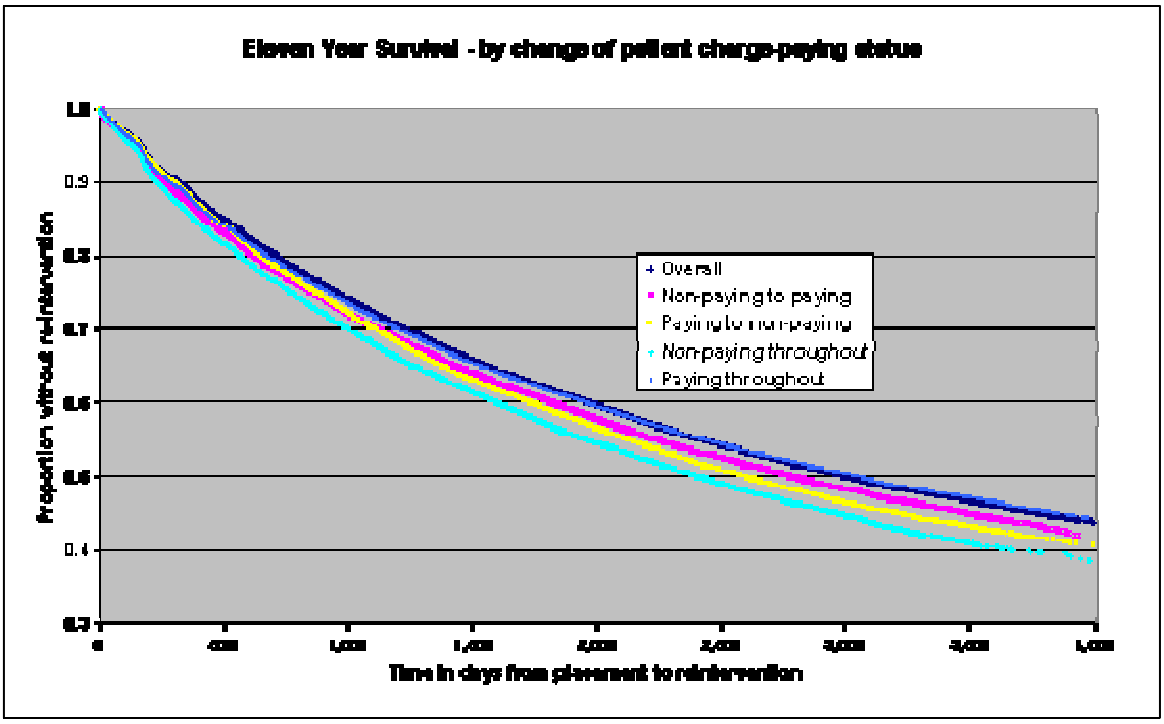


Finally, Table 4.66 and Figure 4.42 show the relationship with subsequent changes in patient charge-paying status. Again, restorations for which the patient made no subsequent attendances were excluded from the analysis. There was a clear differentiation between the four possible subsequent patterns of change, with patients who remained charge-paying throughout experiencing the longest survival of directly placed restorations to re-intervention, and those whose treatment was free throughout having the shortest survival.

Table 4.66 Survival by subsequent change of patient charge-paying status

	Percentiles (days)		Survival Rates		
Change of charge-paying status?	Upper Quartile	Median	I year	5 Year	10 Year
Non-paying to paying	854	2,780	87%	60%	44%
Paying to non-paying	865	2,586	88%	59%	42%
No change non-paying	765	2,409	85%	57%	40%
No change paying	908	3,031	88%	61%	46%

Figure 4.42 Eleven year survival by change of patient charge-paying status



4.3.3 Type of Re-intervention Over Time

Figure 4.43 shows the variation of type of re-intervention over time, totalled across all types of direct placed restorations. The time interval for the steps on the chart is four weeks. The pattern has been presented in the form of a 100% stacked bar chart, showing the proportion of re-interventions of each type after a given interval between interventions. It should be noted that because of the relatively small number of re-intervention intervals in excess of ten years, the chart is subject to a large sampling error after ten years.

Nevertheless, it can be clearly seen that there is a big difference between the pattern for the first year or two and that for the remainder of the chart. For early re-interventions, the proportion of extractions and crowns was much higher, and the proportion of amalgam fillings much lower, than for interventions after more than two years.

The following charts break down the pattern into the components attributable to the three main filling materials: dental amalgam, composite resin, and glass ionomer.

Figure 4.43 Type of re-intervention over time – all restorations

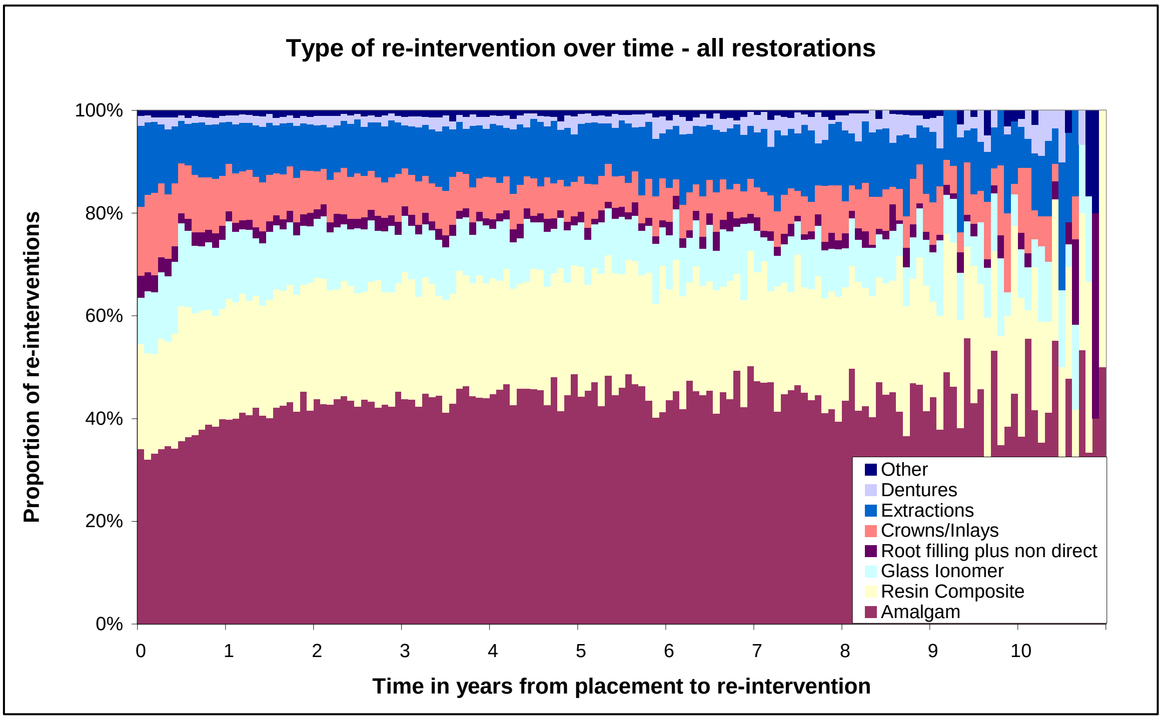


Figure 4.44 Type of re-intervention over time – amalgam restorations

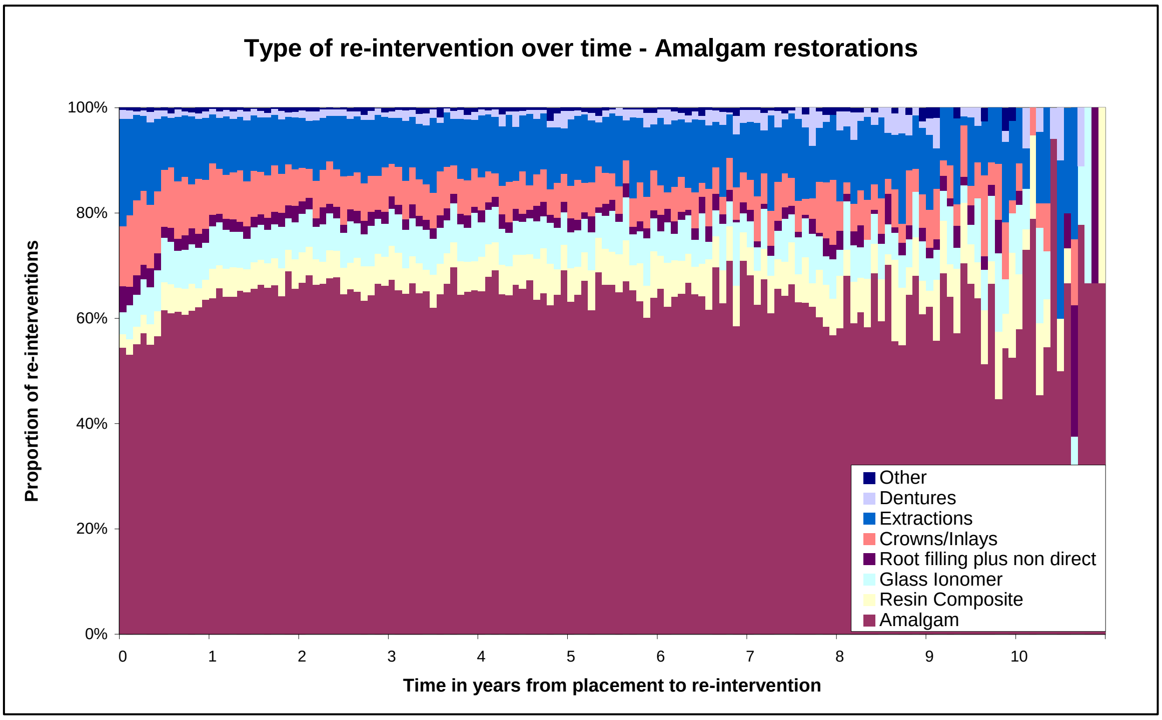


Figure 4.44 shows that this general pattern applies particularly well to amalgam restorations, with a peak re-intervention by amalgam frequency at two years, and heavy incidence of extractions and crowns prior to that.

Figure 4.45 Type of re-intervention over time – resin composite restorations

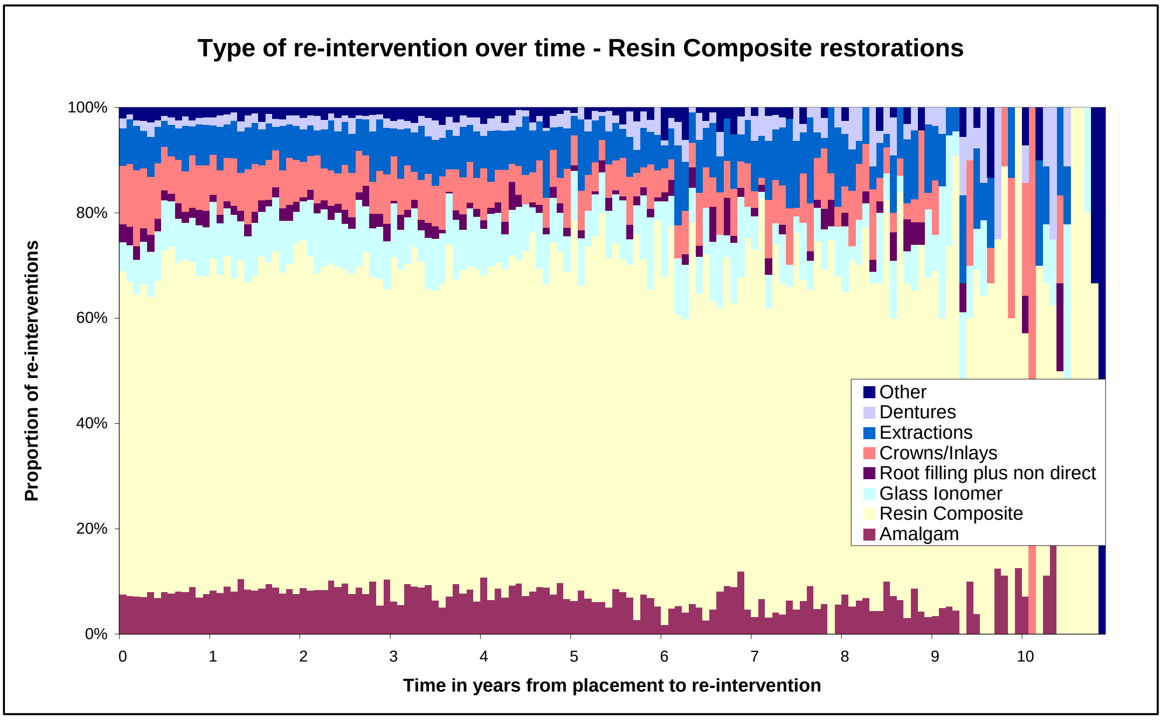
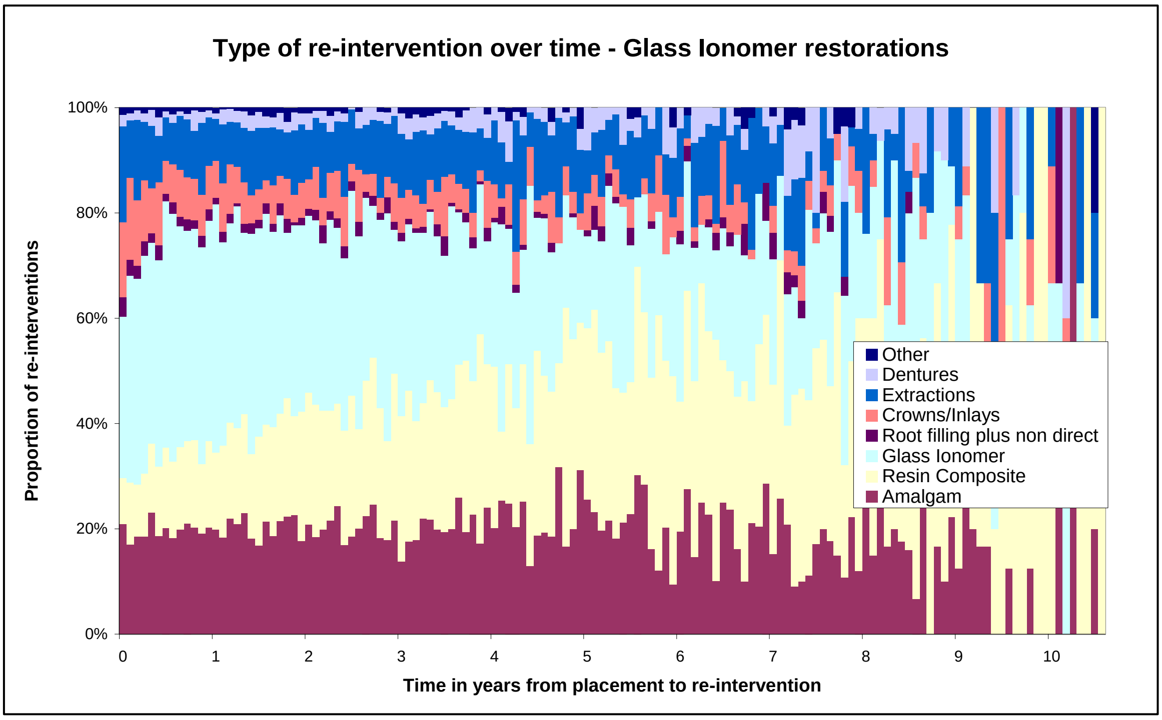


Figure 4.45 shows that the pattern is much less marked for composite resin restorations, with the main feature of interest being the increased incidence of re-treatment with crowns in the event of re-intervention within six months.

By contrast, Figure 4.46 shows that glass ionomer restorations had a much more complex pattern of re-intervention type. A high proportion of early re-interventions involved the provision of crowns. There was also steady growth over the first six years in the proportion whose next re-intervention was composite resin. Indeed, after five years more glass ionomer restored teeth were next treated with composite resin than were re-treated with glass ionomer

Figure 4.46 Type of re-intervention over time – glass ionomer restorations



4.3.5 Interesting Subgroups

This section explores the time to re-intervention for some of the groups of restorations defined by combinations of those variables which appear, from the univariate analyses, to be associated with wide variations in the hazard of re-intervention. Some of these variables, such as tooth position and type of treatment are likely to be correlated. By restricting the data analysed to specific combinations it is possible to examine whether other variables, such as patient or dentist age, continue to have the same association with the re-intervention hazard.

The opportunity has also been taken to explore further whether there appeared to be any underlying change over time in the life expectancy of restorations, after other factors had been controlled.

The data are presented in the form of charts showing the values of the median, upper quartile, and 90^{th} percentile, in days from placement to re-intervention. For some combinations of variables some of these values, particularly the median, cannot be computed, generally because the median is in excess of eleven years. In the case of combinations involving the year of placement there is of course a systematic restriction on the number of follow-up years of data available.

Only a selection of the combinations which have been examined are illustrated here. The appendix contains the full set of combinations, measured by order statistics at five percentile intervals. The analysis was repeated using random censoring to establish standard errors for the order statistics and log-rank tests of both the grouped and pair-wise variation between values of the variables studied. These standard errors and significance tests are also contained in the appendix.

4.3.5.1. Tooth Position and Treatment Type by Year of Placement

Figure 4.47 and Figure 4.48 present, respectively, the upper quartile and 90th percentile survival for four different combinations of tooth position and type of material. The combinations were chosen because they are frequently carried out in the GDS.

Figure 4.47 Upper quartile by year, tooth position and type of restoration

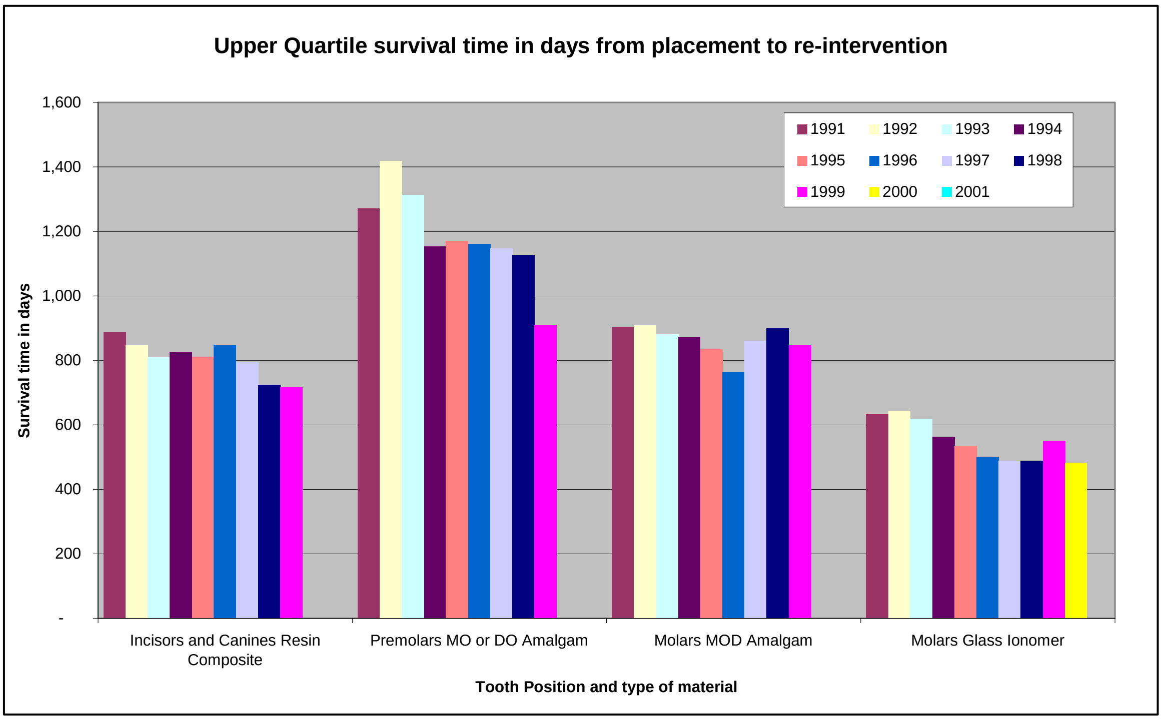
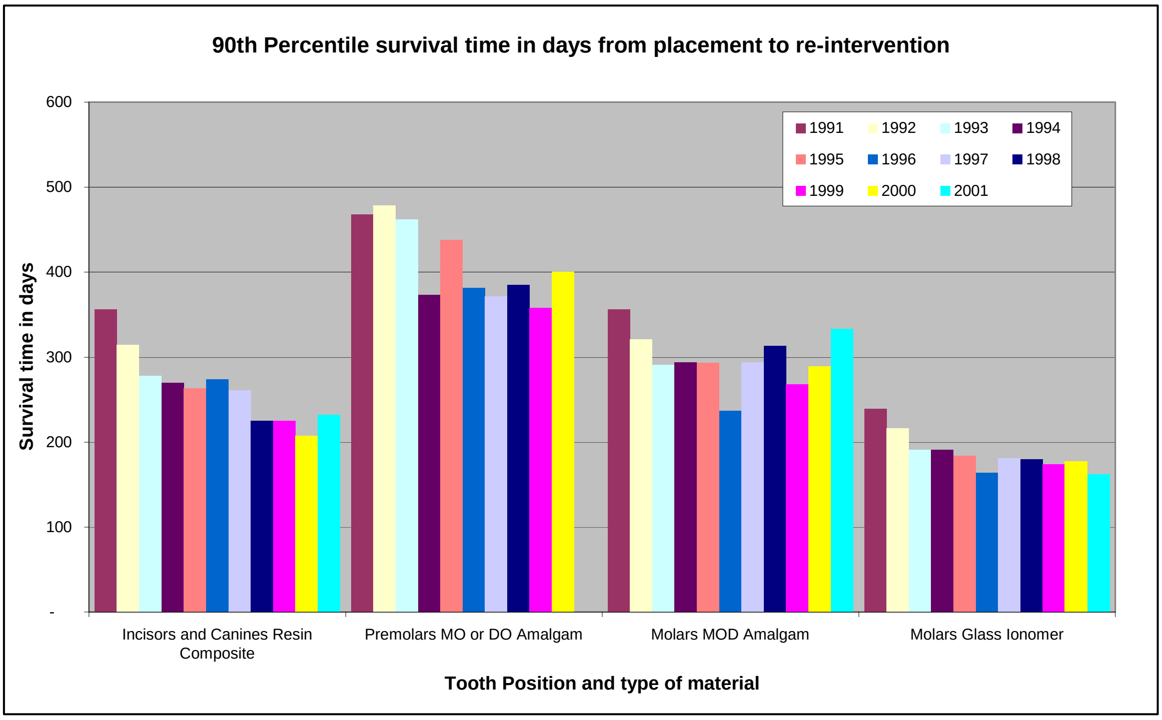


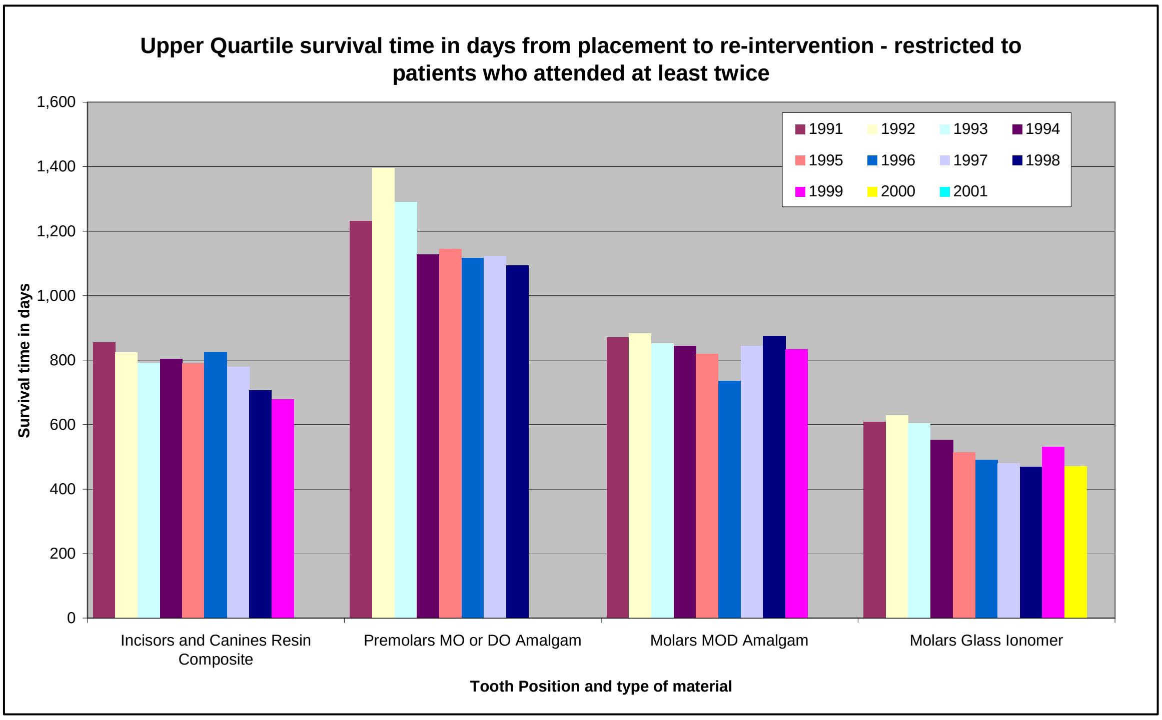
Figure 4.48 90th percentile by year, tooth position and type of restoration



There appears to be an overall reduction in survival by year of placement across three out of the four combinations of tooth position and type of restoration, but not clearly so for MOD amalgams on molar teeth. Most of the pairwise year-on-year comparisons were not significant for adjacent years, but overall the survival curves did differ significantly by year of placement, on incisors and canines for all types of restoration except 1402 (two surface amalgam, not MO or DO), on premolars for MO/DO and MOD amalgams and Class V glass ionomer, and on molar teeth for MO/DO amalgams and Class V glass ionomers. With the exception of MOD amalgams on molar teeth, the absence of significance may be attributable to sample size.

It is conceivable that the apparent overall reduction in time to next intervention with year of placement could be related to changes in the accuracy of identifying patients, so that there may have been more ‘single attendance’ restorations placed in earlier years. However, as Figure 4.49 shows, removing such patients from the analysis, while slightly reducing all the estimates of survival, did nothing to remove the downward gradient, of around twenty per cent over eight years, within each combination of tooth position and type of restoration.

Figure 4.49 Upper quartile restricted to multiple attendance patients



4.3.5.2. Year of Placement by Patient Age by Tooth Position and Treatment Type

The proportions of patients of different ages may also have changed over time, so the next six charts illustrate the pattern when patient age was also controlled. Figure 4.50 and Figure 4.51 show that for composite resin fillings on anterior teeth most, but not all of the downward gradient was eliminated. For this group of restoration types, the reduction with patient age was concentrated in the age range from 40 to 70.

Again the differences between adjacent years of placement were not generally significant, but overall log-rank tests indicated significant differences attributable to year of placement at the 5% level for all patient age groups except the 50-59 group.

Figure 4.50 Composite resin upper quartile

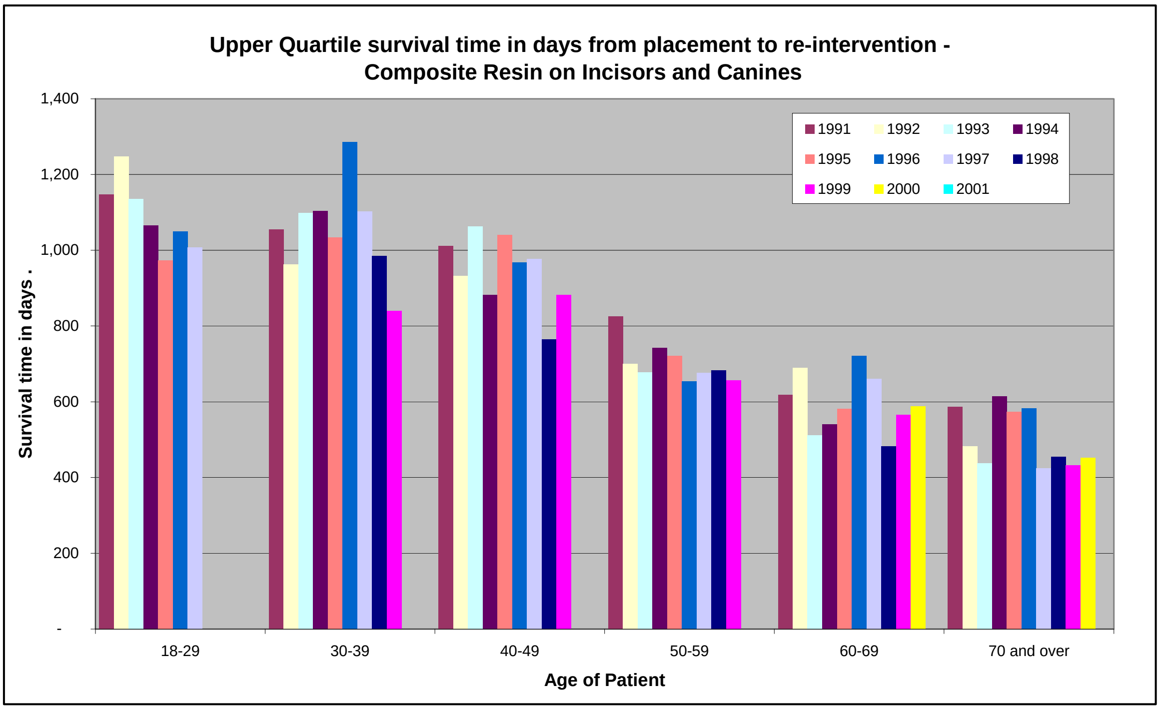
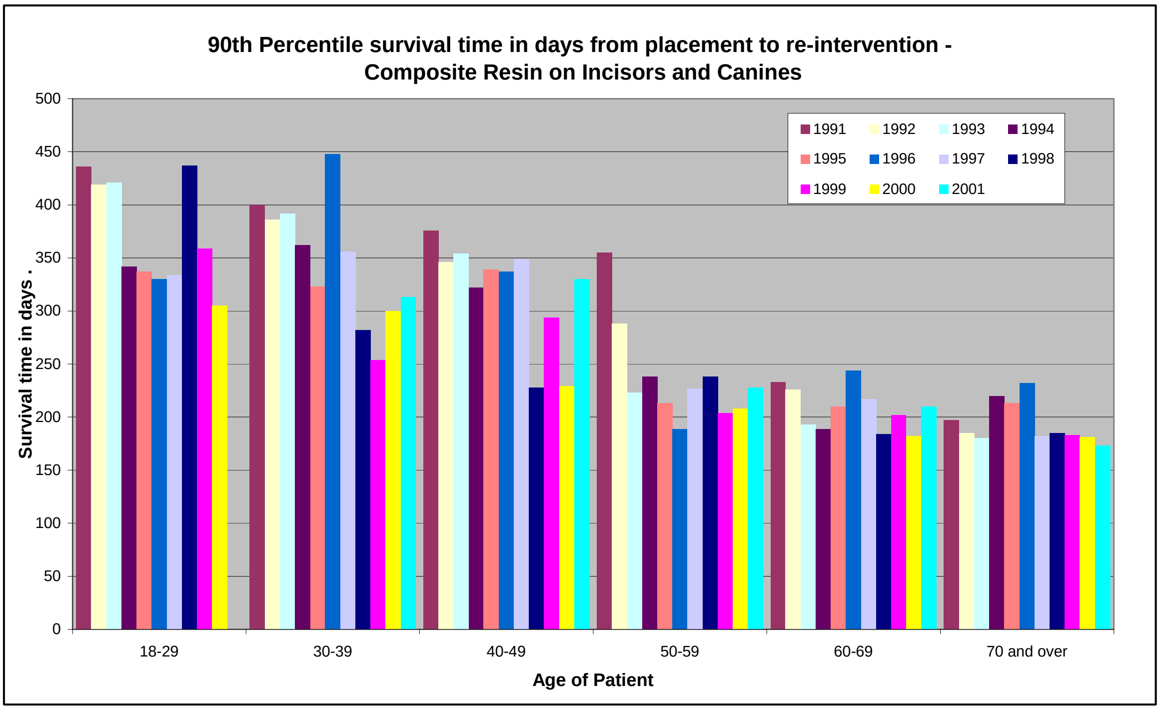


Figure 4.51 Composite resin 90th percentile



For amalgam restorations on molar teeth (Figure 4.52 and Figure 4.53) there was little evidence of a downward correlation with year of placement, at least after the first year. Only three of the patient age groups had significant overall log-rank statistics with respect to year of placement, and one of these – patients aged 18 to 29 – had a pattern of increasing survival by year of placement. There was a clear reduction with age of patient, but associated with an earlier age range than for composite resin on incisors and canines – patients aged under 50.

Figure 4.52 Amalgam on molars - upper quartile

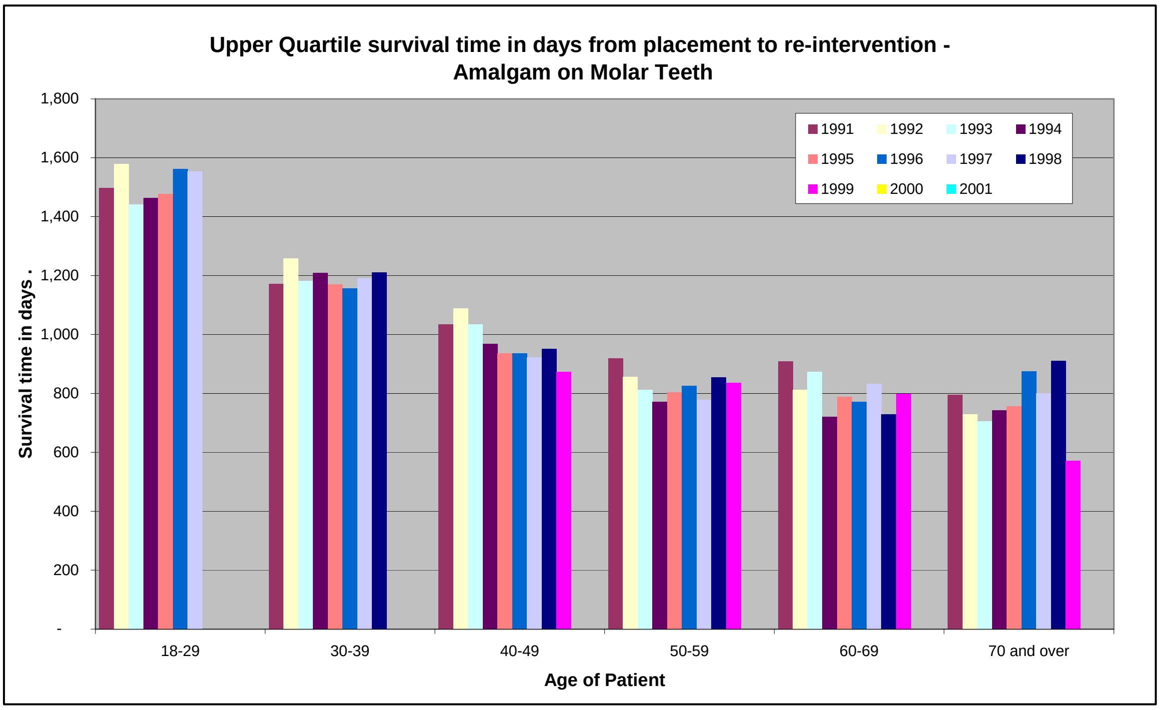
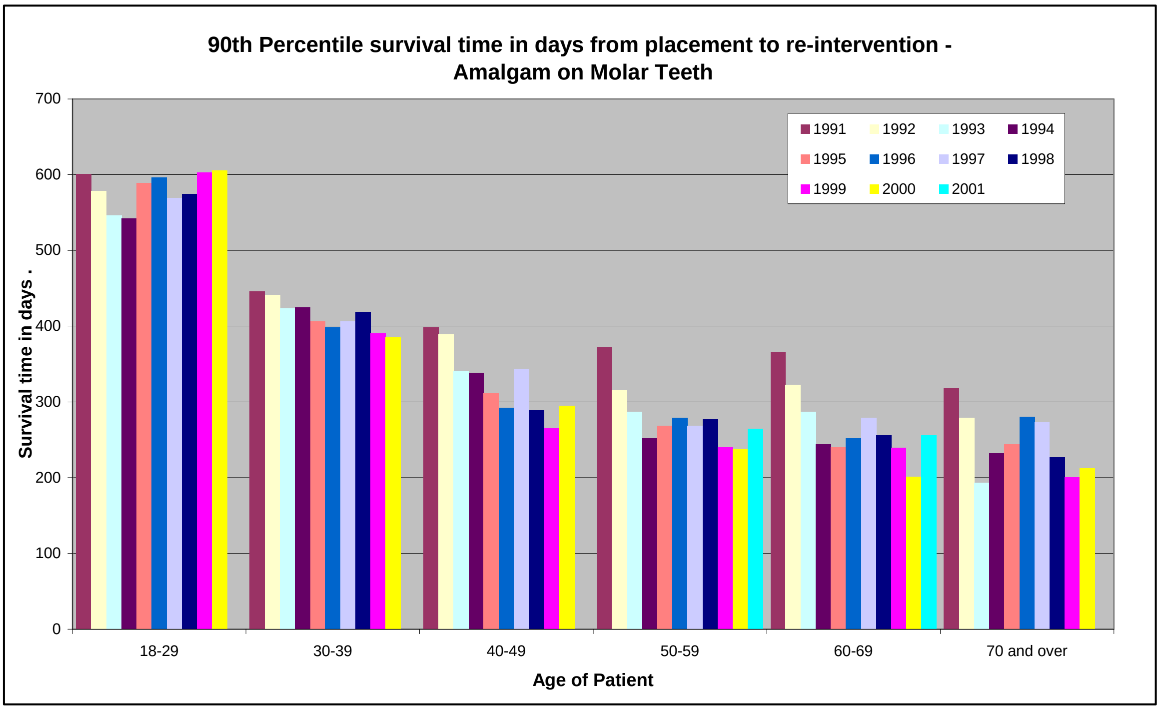


Figure 4.53 Amalgam on molars - 90th percentile



The picture with glass ionomer restorations on molar teeth (Figure 4.54 and Figure 4.55) was subject to considerable fluctuation from one year of placement to the next. Only two out of the six age groups had significant overall log-rank statistics for year of placement – for patients aged between 50 and 69. For glass ionomer fillings the patient age effect was discernible only for the youngest patients – those aged under 40.

Figure 4.54 Glass ionomer on molars - upper quartile

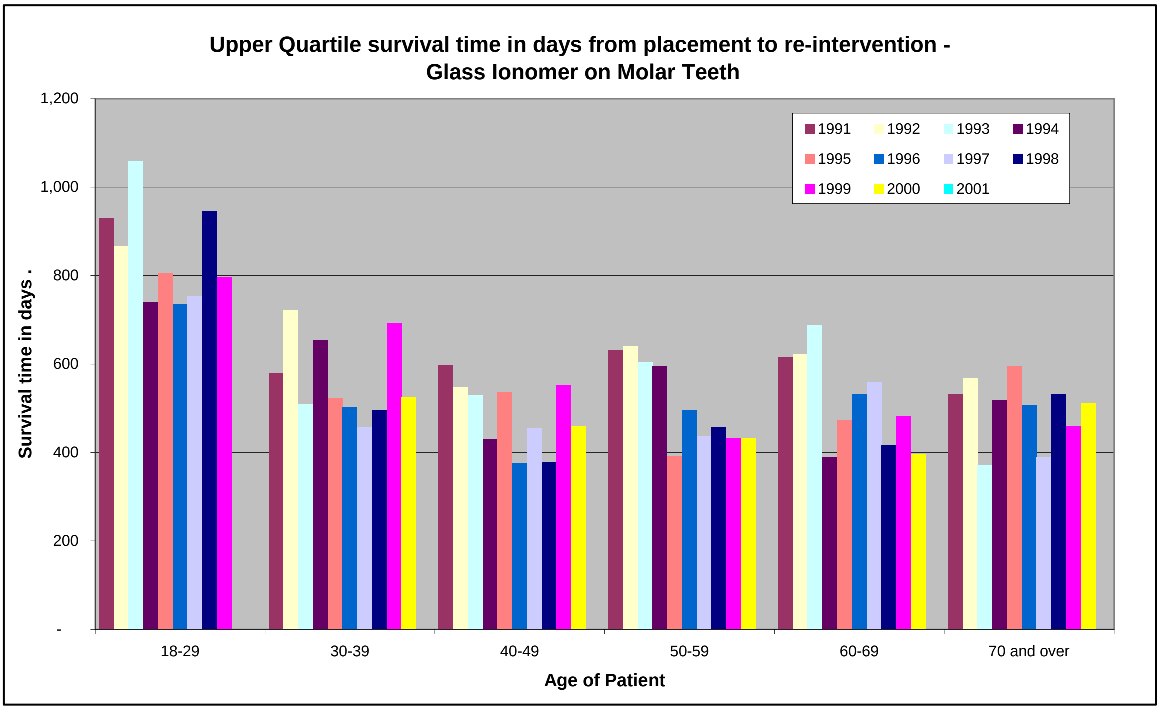
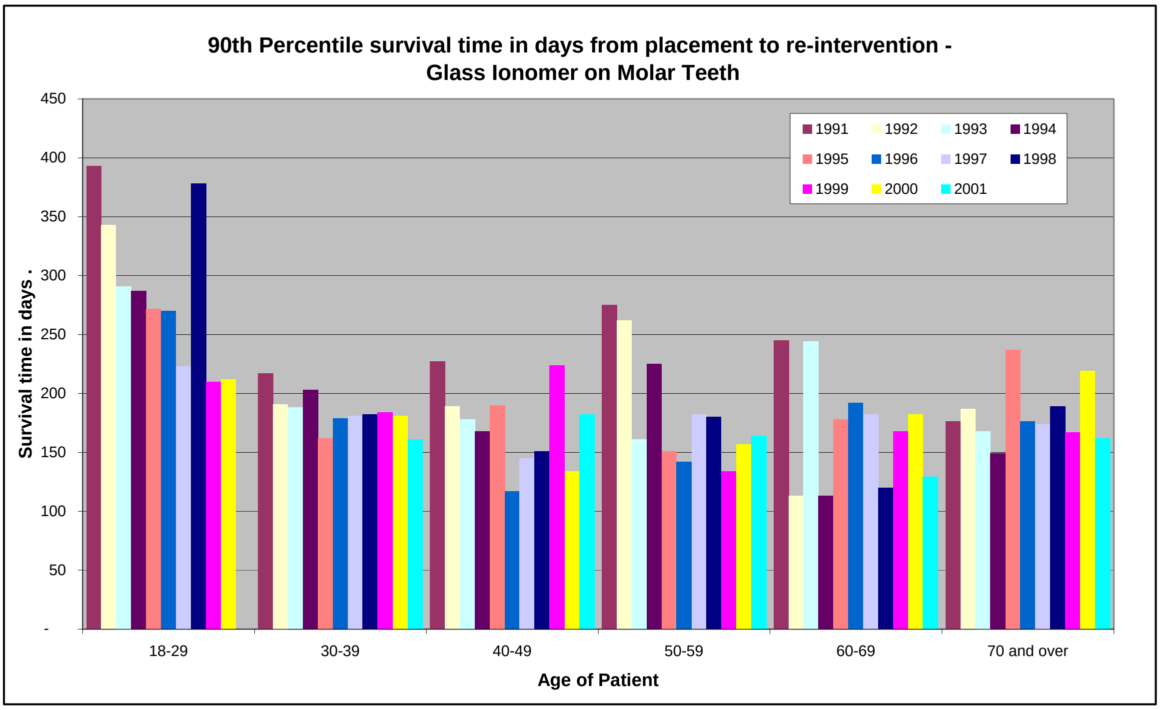


Figure 4.55 Glass ionomer on molars - 90th percentile



4.3.5.3. Dentist Age and Patient Age

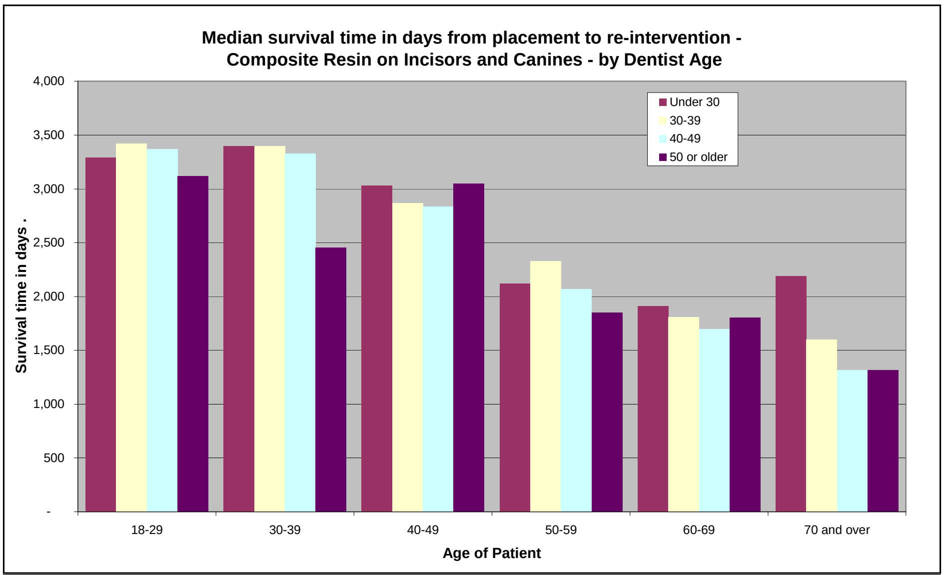
The charts in this subsection show, for the same three combinations of tooth position and restoration type, the relationship between age of patient and age of dentist with respect to median, upper quartile and 90th percentile survival from restoration to re-intervention.

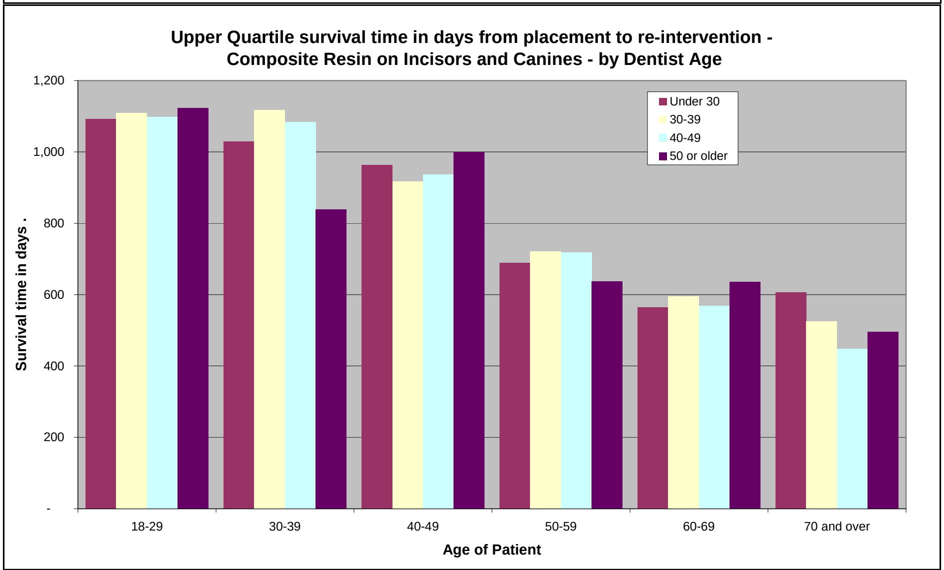
Figure 4.56 shows little sign of any consistent difference in survival within each patient age group with respect to dentist age, for composite resin restorations of incisors and canine teeth. Three of the six patient age groups had significant log-rank statistics with respect to dentist age – 30 to 39, 50 to 59 and 70 or older – though in each case the oldest dentists were associated with the shortest survival.

For amalgam fillings on molar teeth (Figure 4.57) there was a clear inverse correlation between the age of the dentist and the survival time to re-intervention. This became progressively clearer with increasing time after placement. All bar one (age 50 to 59 with p=0.054) of the six overall log-rank statistics were significant at the five per cent level.

For glass ionomer restorations in class V molar cavities (Figure 4.58) the relative position of the different dentist age groups reversed with increasing survival time. At the 90th percentile the patients of the older dentists had better survival, but by the median the youngest dentists had better results than the oldest, in most patient age groups. Only one of the log-rank tests, for patients aged over 70, was significant at the five per cent level.

Figure 4.56 Anterior composite resin by dentist age and patient age





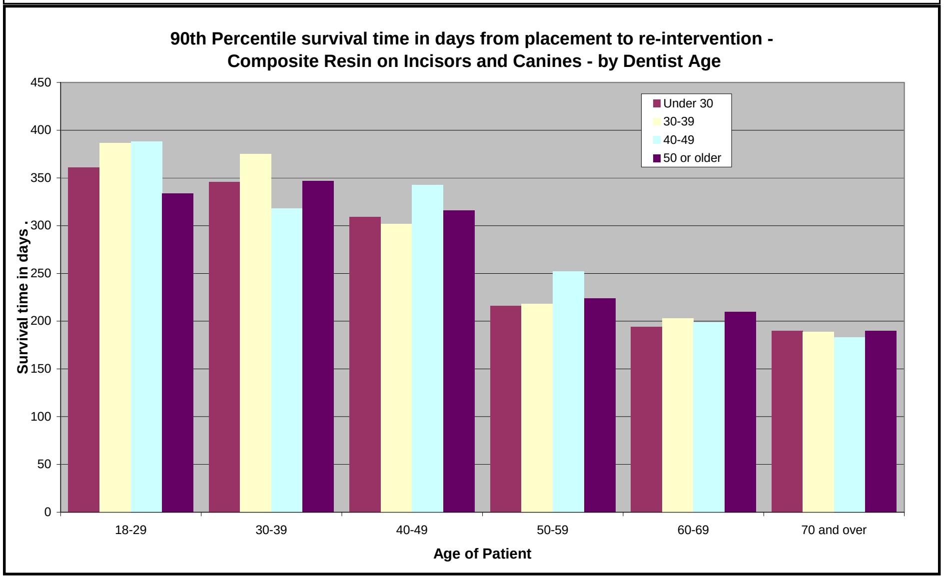
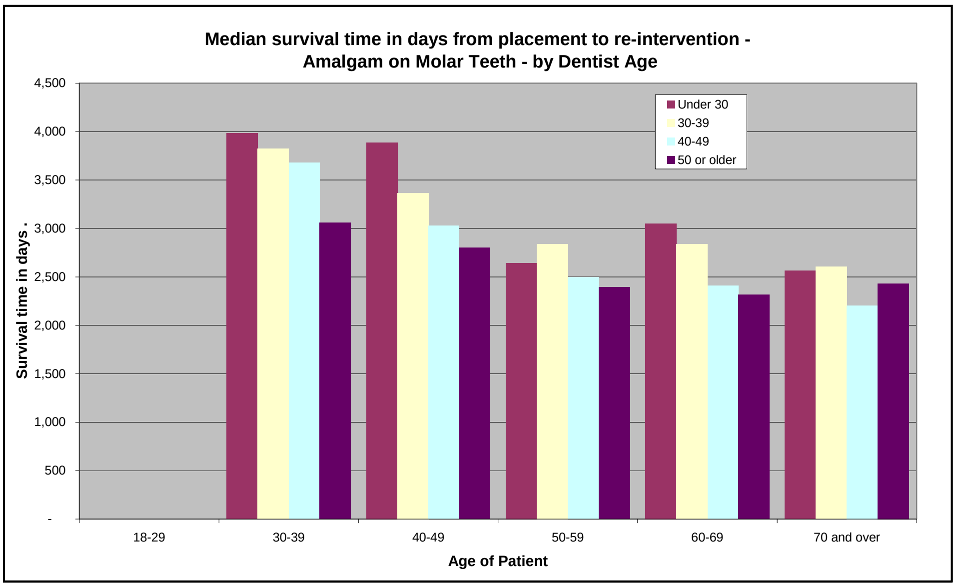
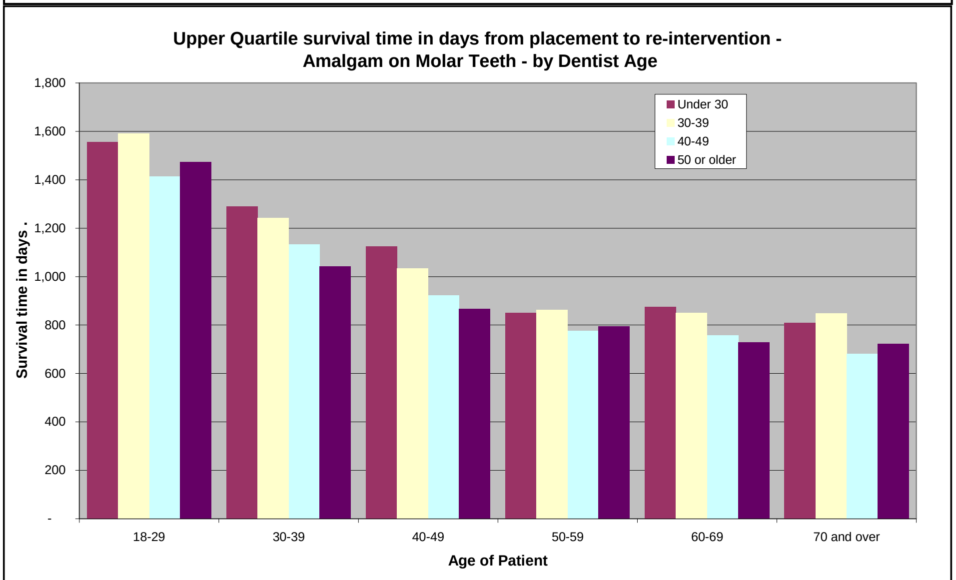


Figure 4.57 Molar amalgam by dentist age and patient age





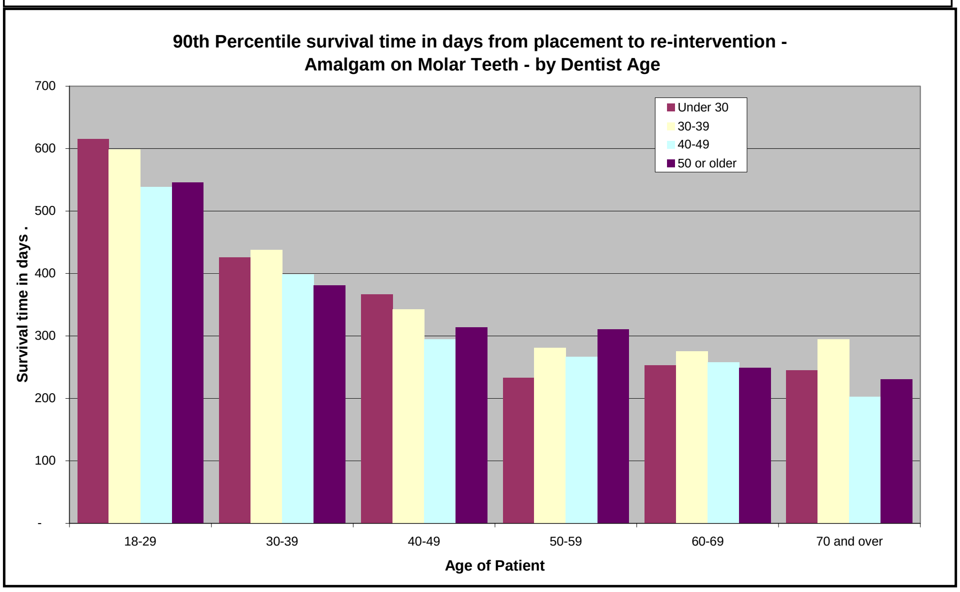
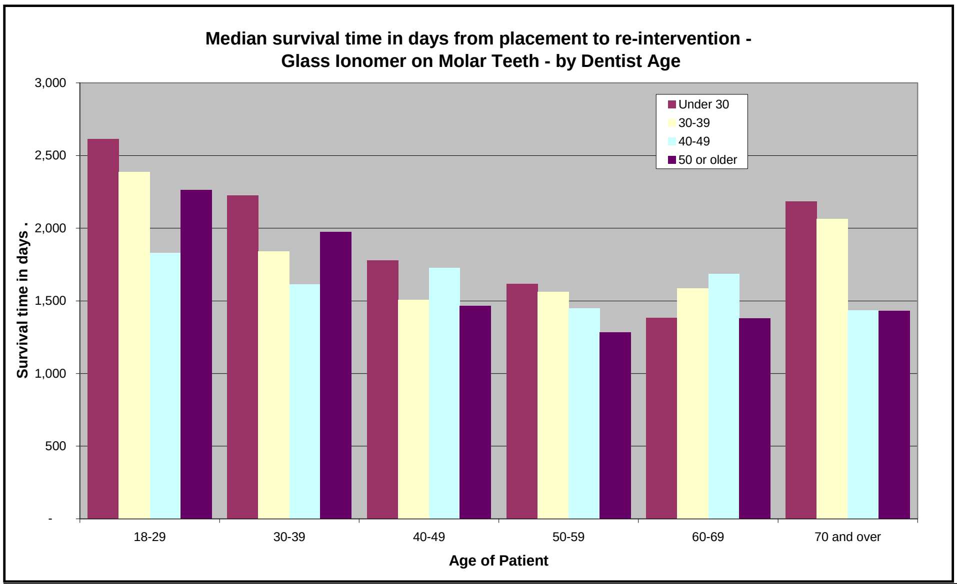
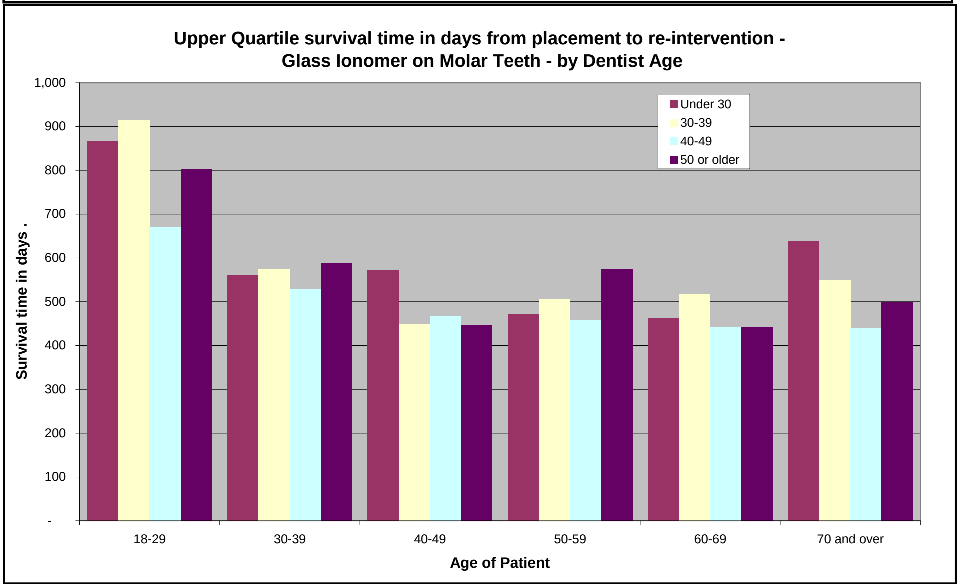
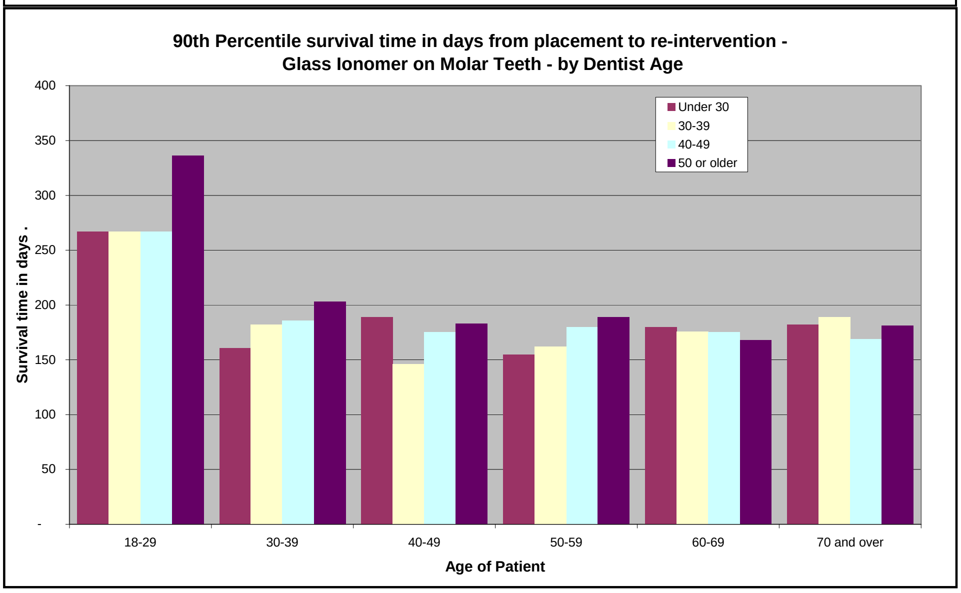


Figure 4.58 Molar glass ionomer by dentist age and patient age







4.3.5.4. Mean Annual Cost and Patient Age

These charts show the extent to which the survival of a restoration to next re-intervention was associated with the combination of patient age and the mean annual scale fees for that patient. Mean annual fees could be calculated only if the patient had attended at least twice.

For composite resin on anterior teeth (Figure 4.59), mean annual cost was inversely related to survival, in all patient age groups. However, within each cost group, there was little change with age of patient, except for patients aged over 50.

For amalgams on molar teeth (Figure 4.60) there was a steady reduction in survival, both with mean annual cost and with age of patient.

For glass ionomer class V molar restorations (Figure 4.61) there was no consistent relationship between patient age and survival, although within each patient age group there was clear evidence of an inverse relationship between annual cost and survival.

For all patient ages and types of restoration the overall log-rank tests were highly significant with respect to mean annual cost.

Figure 4.59 Anterior composite resin by annual cost and patient age

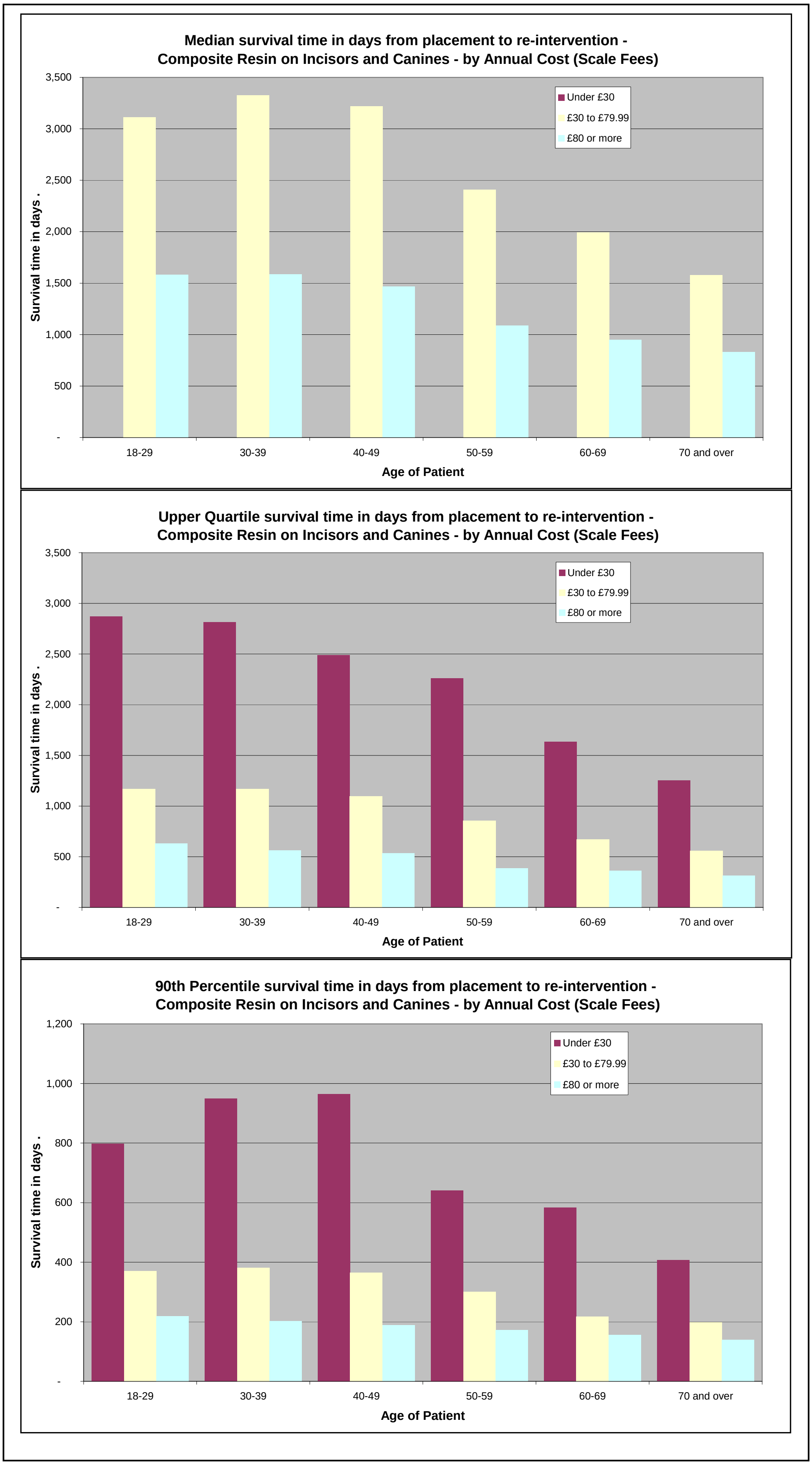


Figure 4.60 Molar amalgam by annual cost and patient age

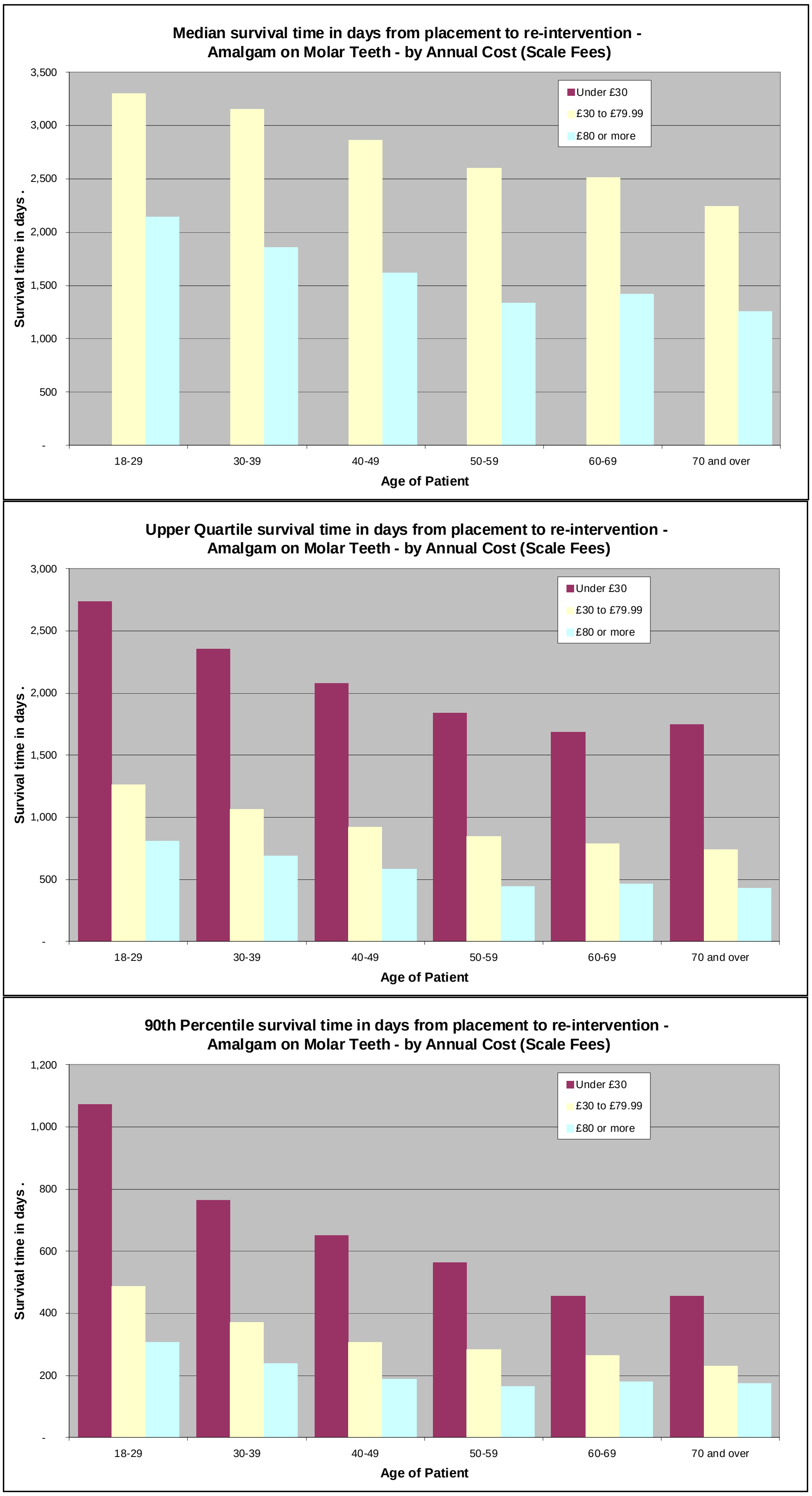
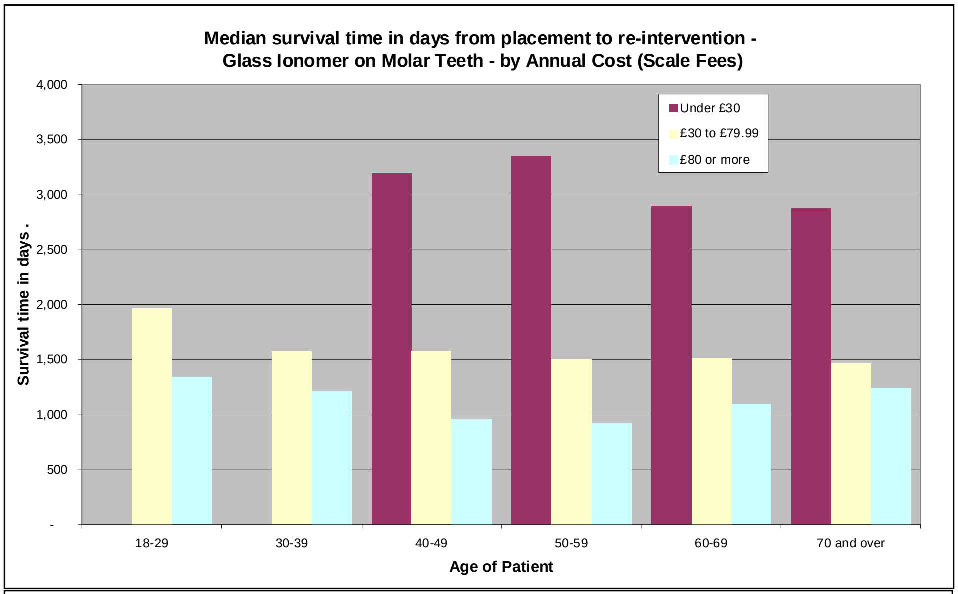
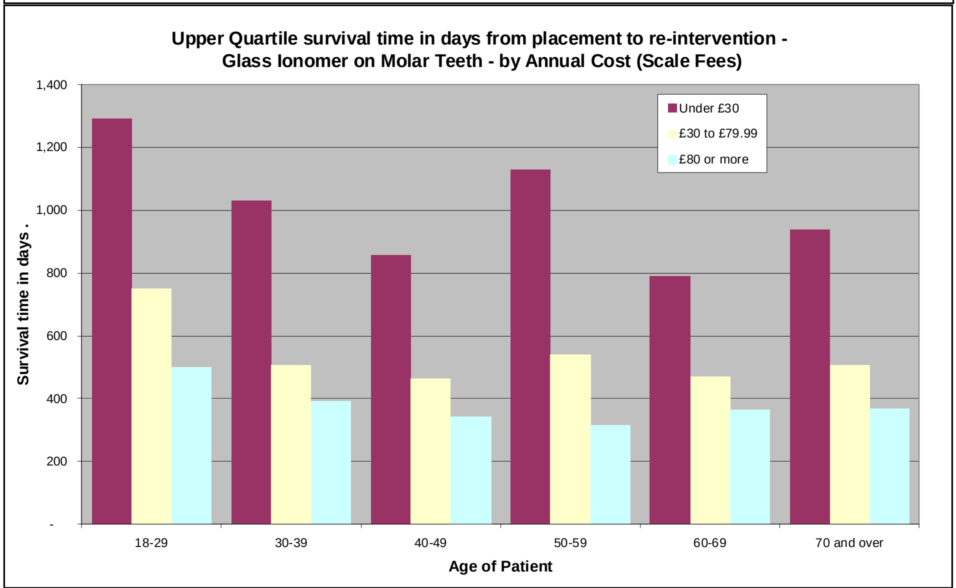
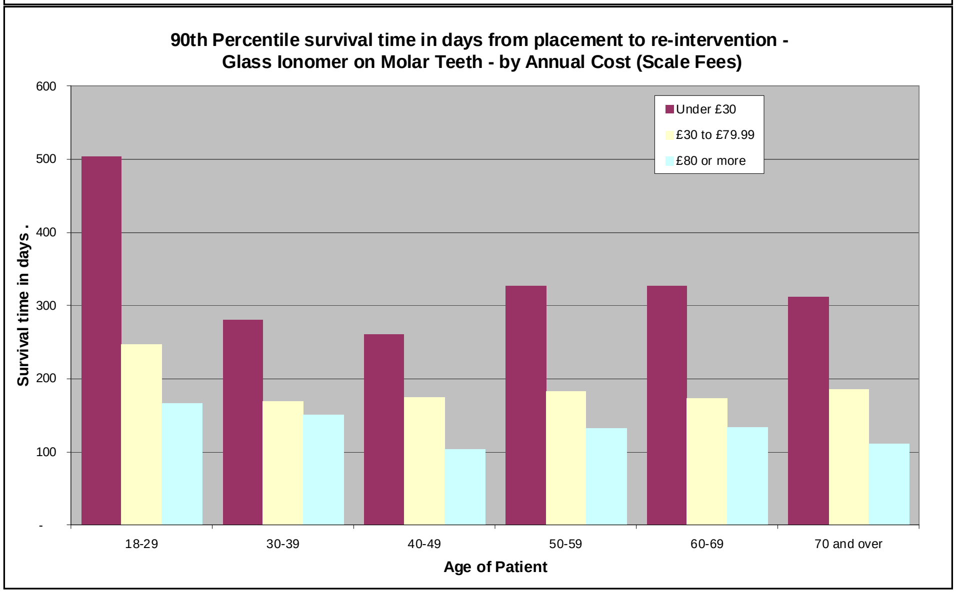


Figure 4.61 Molar glass ionomer by annual cost and patient age







4.3.5.5. Median Claim Interval and Patient Age

A similar analysis has been carried out using median interval between claims instead of mean annual cost. The same three combinations of treatment type and tooth position were used, and again the charts show the median, upper quartile and 90^{th} percentile survival to next intervention.

For composite resin on anterior teeth (Figure 4.62), median claim interval was positively correlated with survival, in all patient age groups. However, within each claim interval group, there was little change with age of patient, except for patients aged over 50.

For amalgams on molar teeth (Figure 4.63) there was a steady improvement in survival within each patient age group with increasing interval between claims, and a steady reduction in survival with increasing age of patient within each median claim interval group.

For glass ionomer class V molar restorations (Figure 4.64) there was no consistent relationship between patient age and survival, although within each patient age group there was clear evidence of an correlation between median claim interval and survival.

For all patient ages and types of restoration the overall log-rank tests were highly significant with respect to median claim interval.

Figure 4.62 Anterior composite resin by median claim interval and patient age

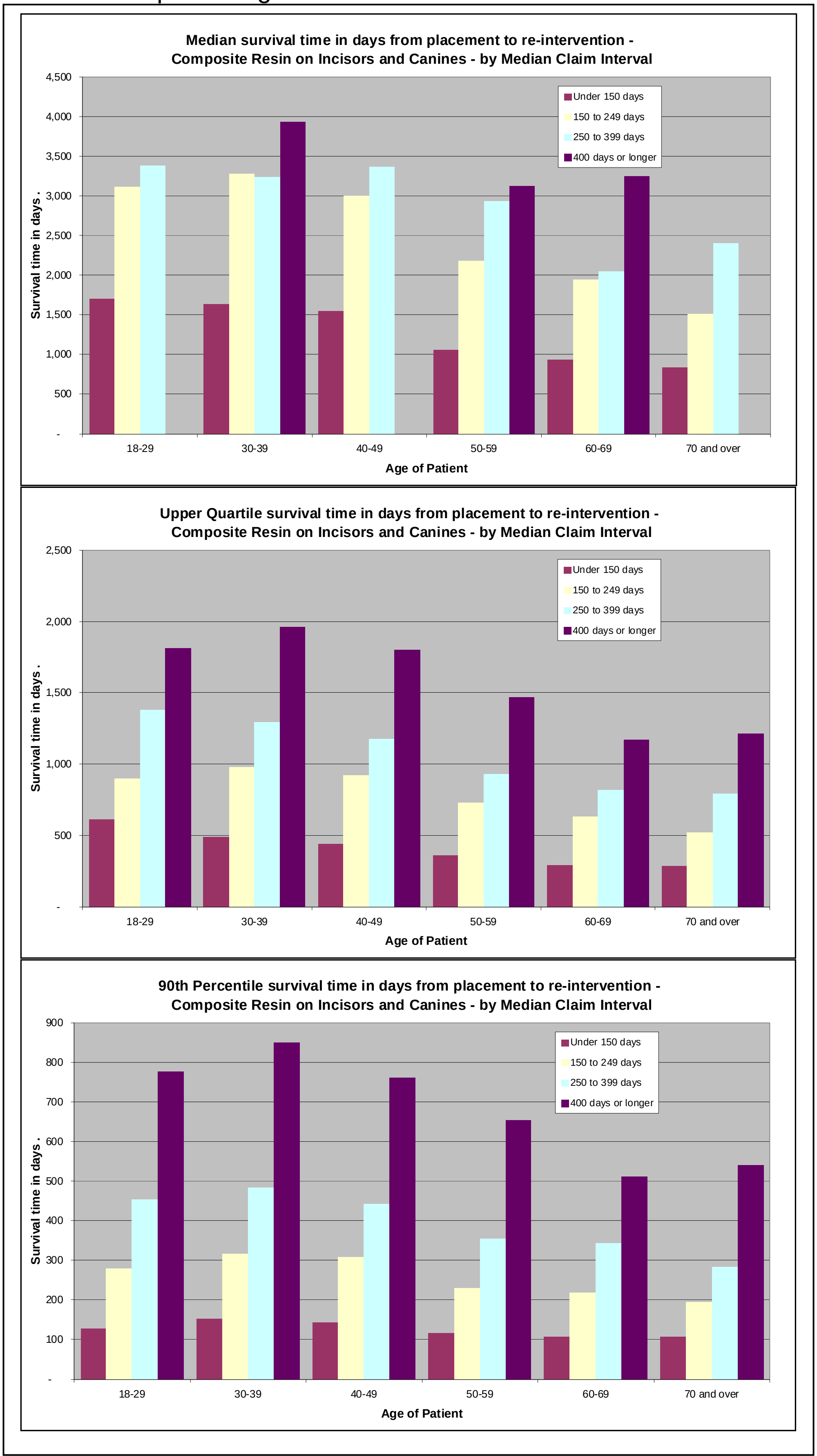


Figure 4.63 Molar amalgam by median claim interval and patient age

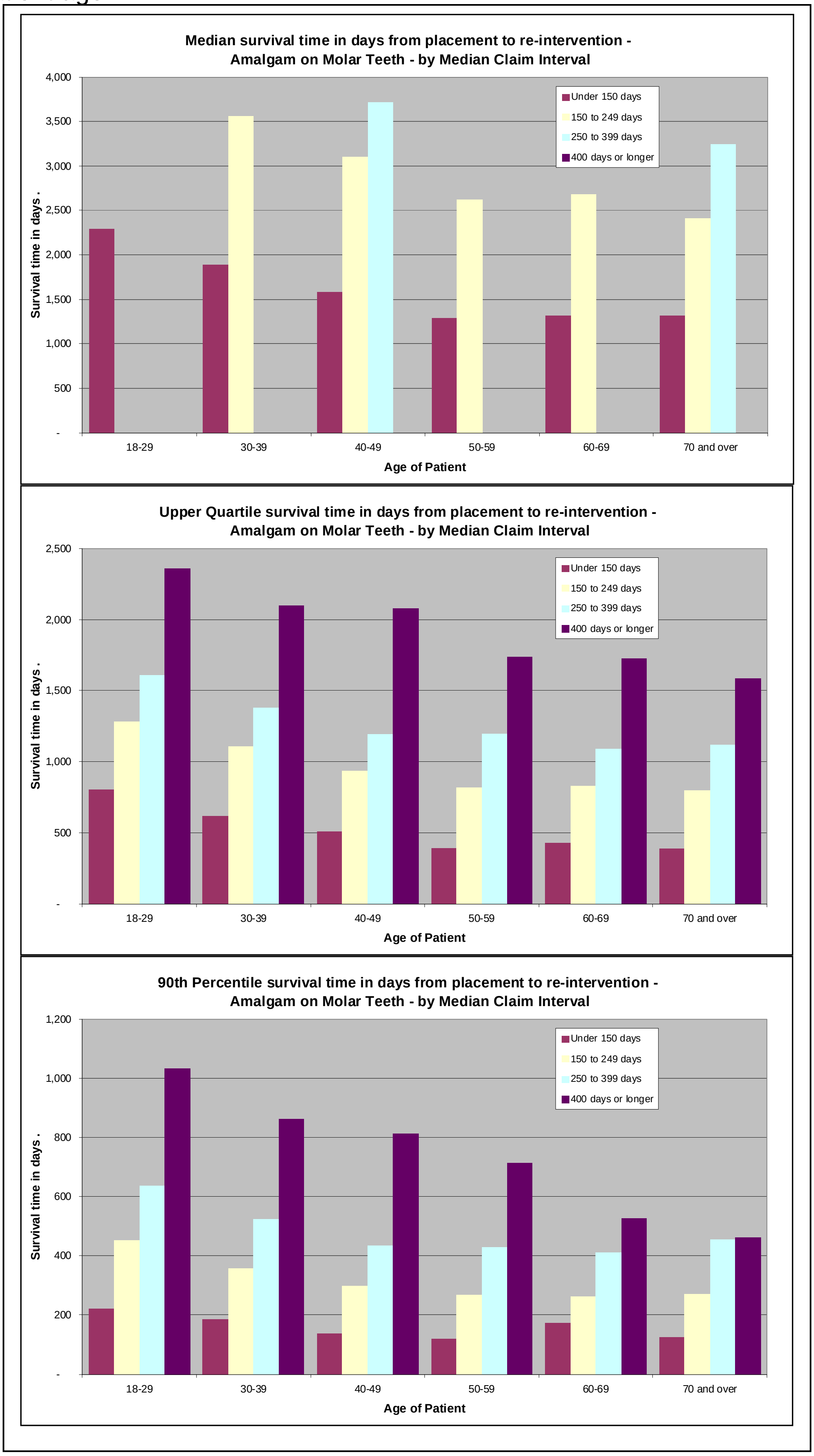
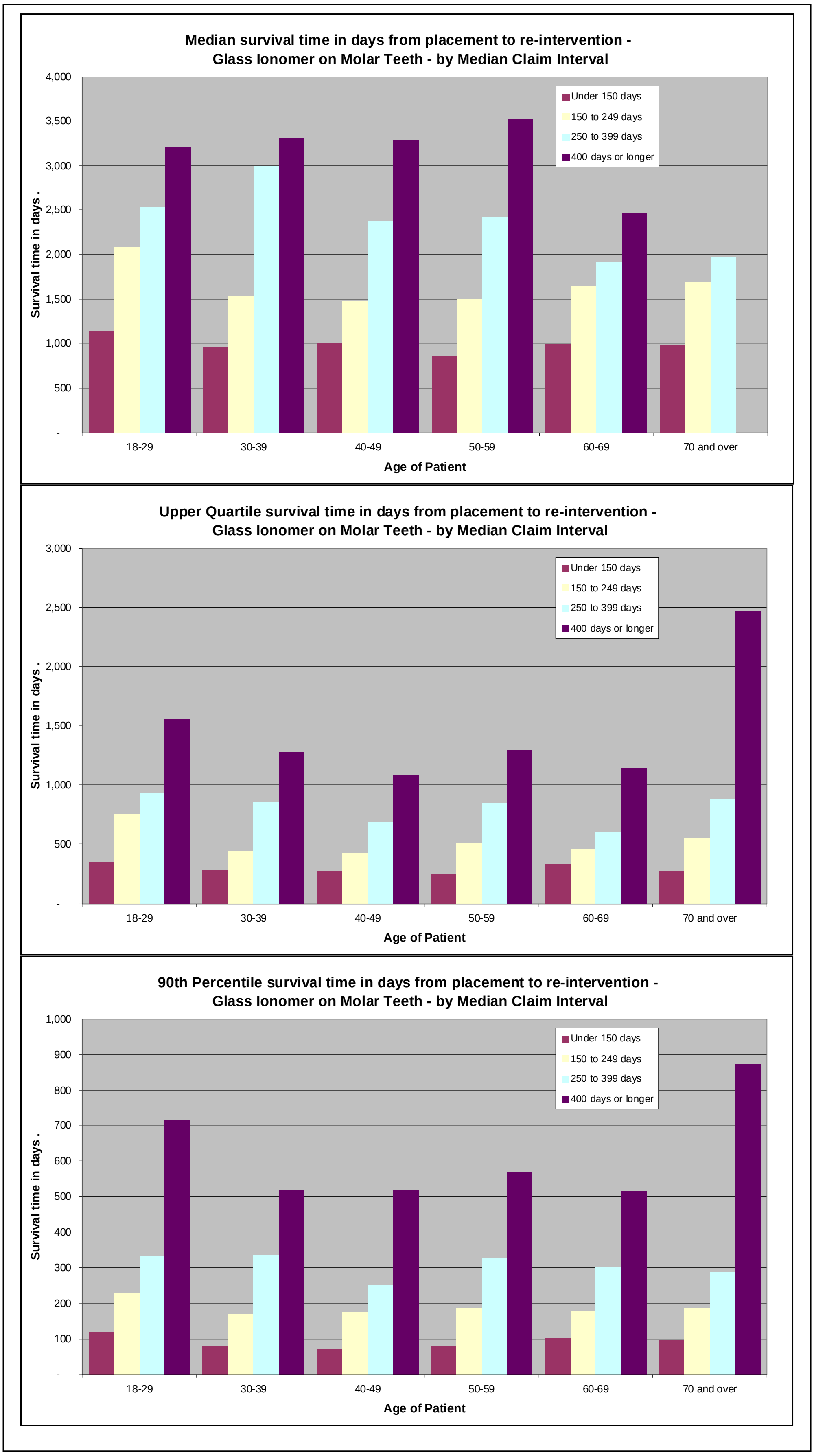


Figure 4.64 Molar glass ionomer by median claim interval and patient age



4.3.5 Replication

Figure 4.65 Eleven year survival - replication

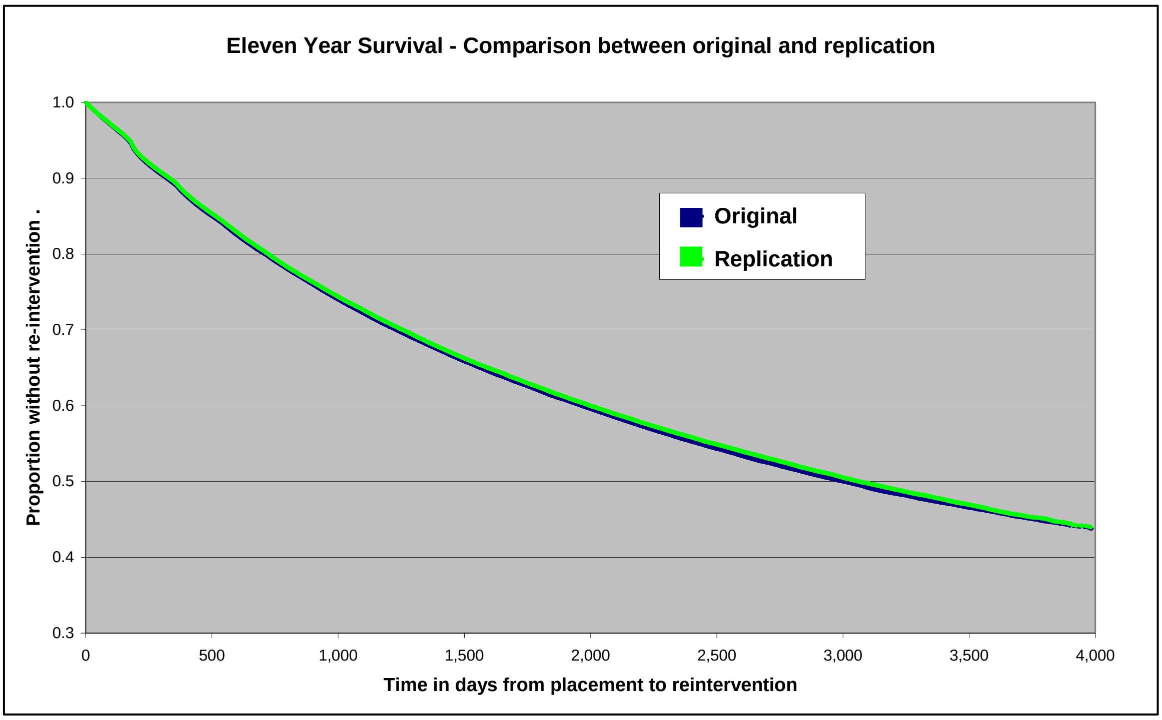


Figure 4.65 shows the overall survival curve for the replication analysis, superimposed on the original curve.

Table 4.67 Comparison of survival rates

Years since restoration	Survival Rate	
	Original	Replication
1	0.887	0.890
2	0.795	0.798
3	0.723	0.727
4	0.664	0.668
5	0.616	0.620
6	0.574	0.579
7	0.538	0.544
8	0.506	0.512
9	0.479	0.484
10	0.456	0.458

Table 4.67 shows the corresponding survival rates to next intervention. The figures have been quoted to three decimal places in order to quantify the differences. The rates at one year, five years and ten years are the same, quoted to two decimal places, as those in the original analysis (Table 4.47).

The full set of replication analyses may be examined in the appendix. Except for some of the more sparsely populated analyses described in section 4.3.5, the agreement between original and replication is close. The Cox-regression analysis described in section 4.4.3 was also conducted, again producing very similar results, similarly documented in the appendix.

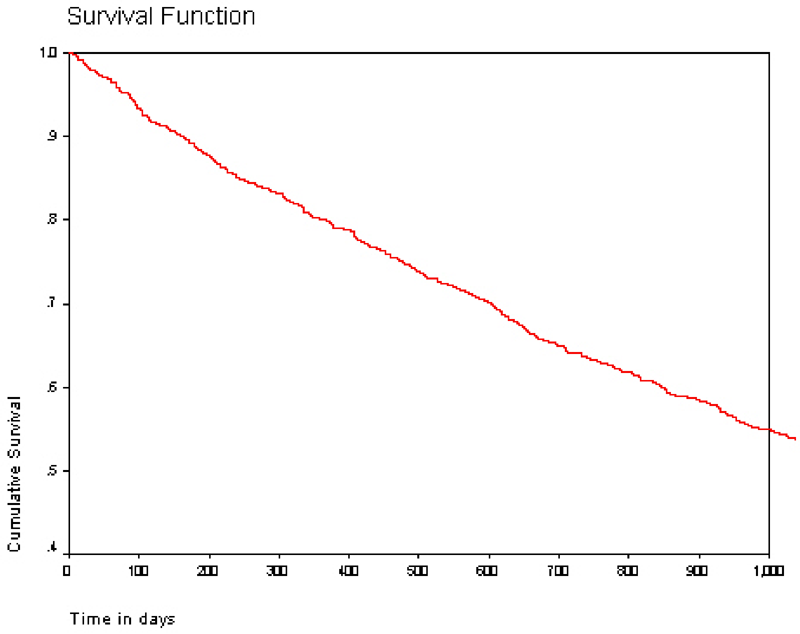
4.4 Modelling and Simulation

4.4.1 The Inflexion at Six Months

The program listings for these two simulations are available in the appendix. Both models consisted of a mixture of cases from two different distributions, one of which was an exponential and the other an interval censored exponential. The simulation involved generating one thousand cases of each distribution and plotting the survival curve for the combined population of two thousand cases.

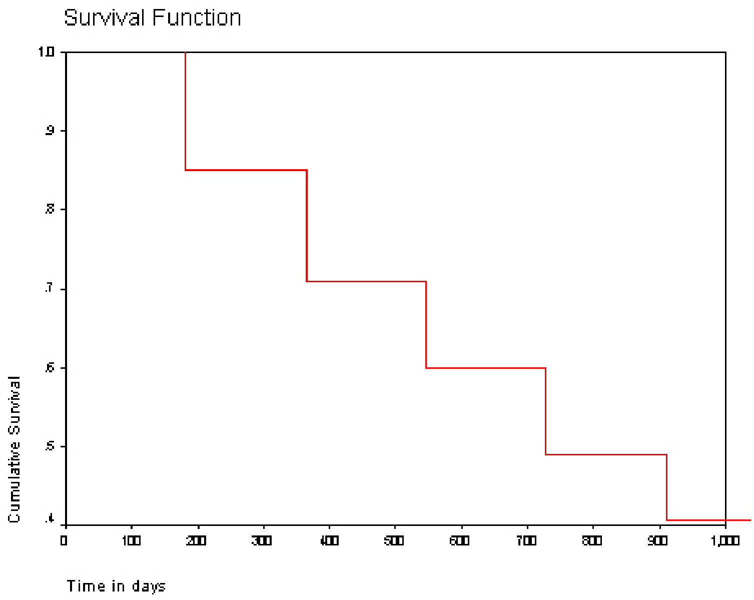
In Simulation 1 the ordinary exponential population had a scale parameter of $\lambda=0.0006$, implying a mean survival time of about 4.5 years. Figure 4.66 illustrates the shape of the survival curve.

Figure 4.66 Survival curve for simulated exponential distribution, with λ = 0.006



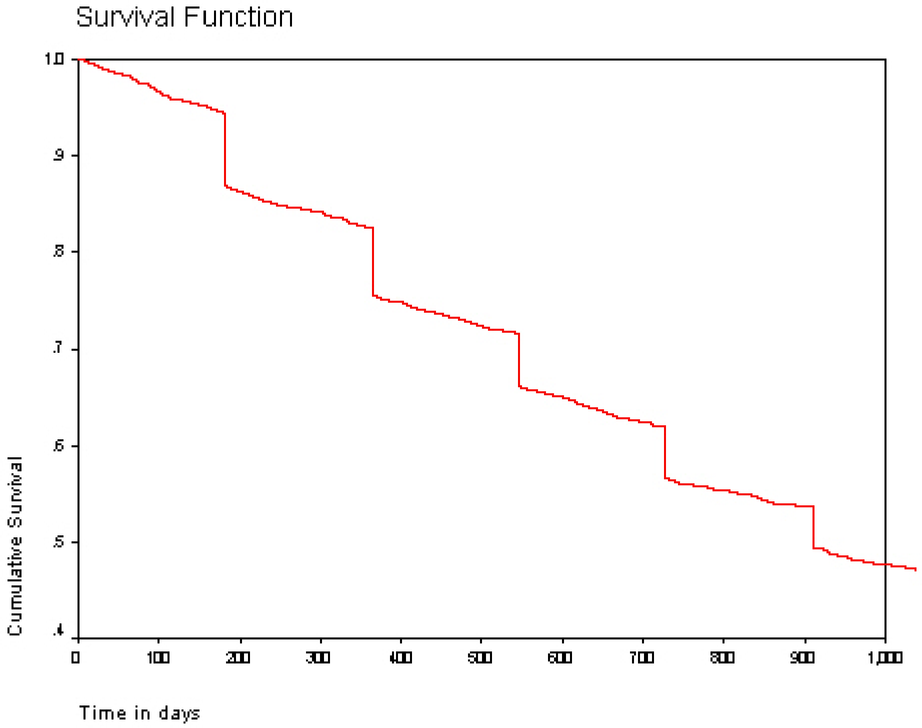
The second distribution was formed by assuming that an exponential distribution with λ=0.001 (which implies a mean of about 2.7 years) was interval censored to the next routine examination. It was assumed that routine examinations occurred at fixed intervals of 182 days (26 weeks). Figure 4.67 illustrates the resulting step function survival curve.

Figure 4.67 Survival curve for simulated fixed interval censored exponential with λ=0.001 and interval = 182 days



The two populations were then combined (in equal proportions) to give Figure 4.68. This has inflexions at six-monthly intervals but the inflexion is very abrupt and there is very little attenuation of the inflexion over successive years.

Figure 4.68 Combined survival curve for exponential and fixed interval exponential simulated populations



Accordingly, for Simulation 2 the censoring interval was itself allowed to vary. The interval was defined as having a fixed minimum of 168 days (24 weeks) and a variable addition comprising an exponential distribution with a mean of 14 days (two weeks). The resulting curve is illustrated in Figure 4.69. The same ‘ordinary’ exponential population was then combined with this variable interval censored population to give Figure 4.70. This curve has the desired characteristics of smoother inflexions and attenuation over time.

Figure 4.69 Survival curve for simulated exponential with variable interval censoring

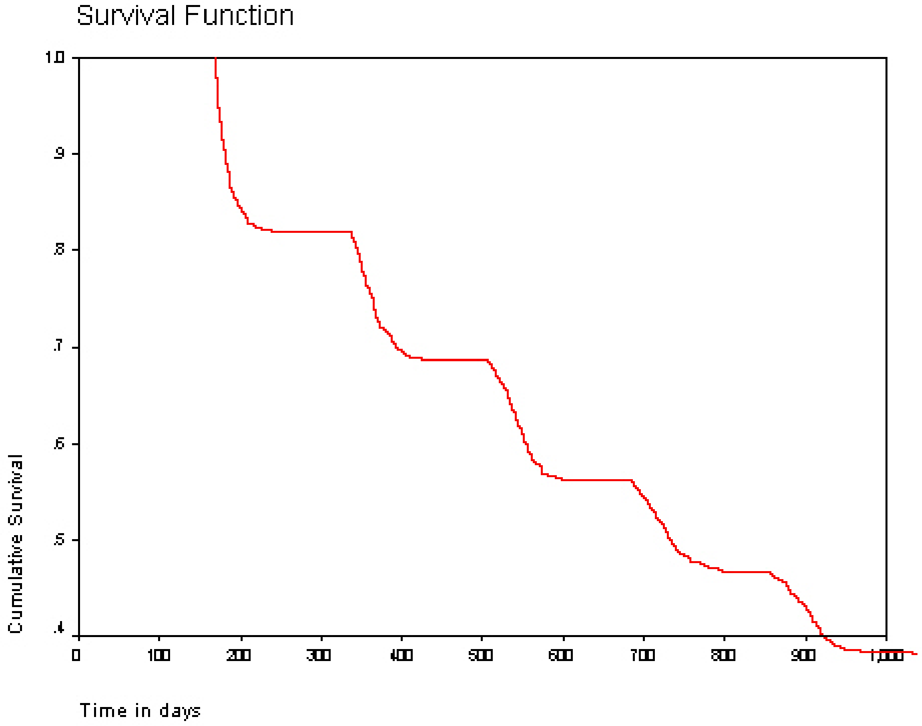
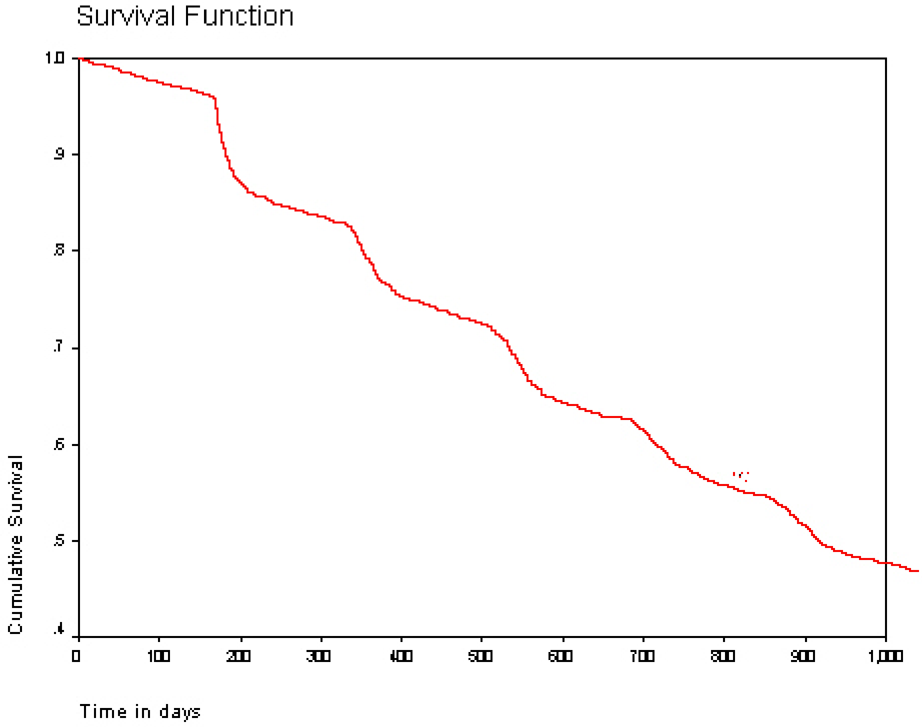


Figure 4.70 Survival function for combination of ordinary exponential and variable interval censored simulated populations



4.4.2 Simulation of Cross-sectional Distortion

The two simulations in this section explore the consequences of treating cross-sectional data as though it came from a complete enumeration of cases from a stable time series, where such treatment is inappropriate. Both simulations assume that the underlying cumulative survival function is linear, starting at one in year zero and reducing evenly to zero in year twenty. A linear survival function has been chosen for simplicity of graphical interpretation – any distortion of a straight line is easy to distinguish.

In the first simulation (Figure 4.71) two historical patterns of change in volume are compared with the underlying distribution. When the volume reduces from 300 units at year zero to 110 at year twenty then the apparent survival curve, inferred from the distribution of times to re-intervention in a cross-sectional survey, then the curve is distorted upwards, suggesting that the expected interval to re-intervention is higher than it really is. Conversely, when the historical pattern is one of steady increase from 110 at year zero to 300 at year twenty, then the curve is distorted downwards, suggesting an unnecessarily gloomy picture.

The second simulation considers the effect of failing to include some of the re-interventions. In this simulation (Figure 4.72) it is assumed that 2,000 restorations are placed each year, of which in each year 5% receive re-intervention. It is then assumed that a proportion of these re-interventions were not observed, because for example they involve an extraction of the tooth. It is assumed that the earlier the re-intervention, the more likely it is to be unobserved. The net effect is that a disproportionate number of the restorations which are replaced are 'old', resulting in a higher estimate of time from placement to re-intervention (whether expressed as an empirical survival curve, median, mean or any other statistic).

Figure 4.71 Distortion resulting from changes in historical volumes of restoration provision

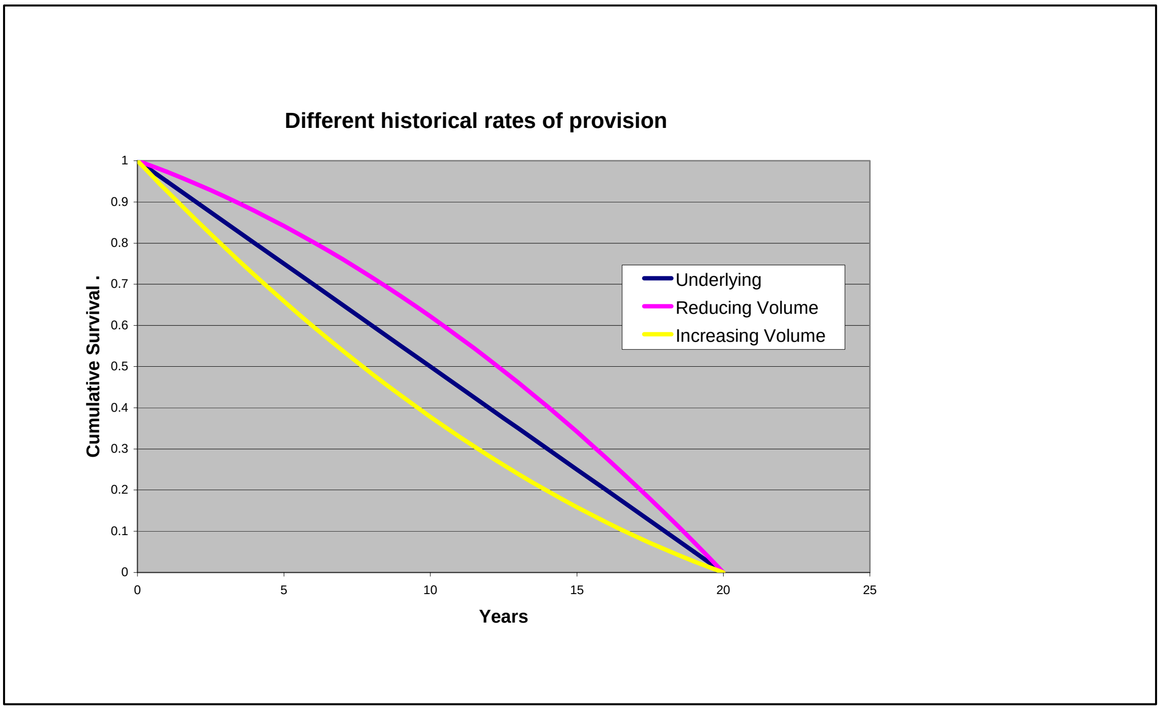


Figure 4.72 Effect of ignoring restorations subject to disproportionately early re-intervention (for example, by extraction)

4.4.3 Cox Regression Model

The sub-sample from the DPB data used for the Cox-regression model contained 260,788 restorations, all placed before 2000 in patients for whom at least four claim records were available and whose last record of attendance was in 2000 or 2001. Tunnel restorations and root fillings without direct restorations were excluded from this subset.

Prior to the Cox-regression analysis a Kaplan-Meier Analysis was run to compare the sub-sample with the main sample used in the univariate analyses. Table 4.68 provides a comparison between the two sample populations. Because the sub-sample excludes those patients who have made only rare attendances, there is a naturally shorter expectation of interval to next intervention among the sub-sample chosen for the model. The standard errors for the model sub-sample are not much greater than those for the full sample (described in section 4.3.3.2), of around 14 days for the median, so the differences are clearly statistically significant.

Table 4.68 Cox-regression sample comparison

Comparison of Kaplan-Meier Cumulative Survival Percentiles between sample for model and overall sample		
Percentile	Time from placement to re-intervention (days)	
	Cox Regression Model Sample	Overall Sample
95	154	168
90	273	321
85	427	500
80	609	709
75	818	949
70	1,057	1,231
65	1,338	1,563
60	1,673	1,965
55	2,067	2,432
50	2,528	3,004
45	3,085	3,771
40	3,857	N/A

Table 4.69 lists all the variables which were entered into the forward stepwise Cox-regression analysis. Only four of these variables, PATAGE, MEANANNF, MEDINT and YEARPLAC, are treated as continuous variables.

The remainder are categorical variables. Where a variable name is followed by one or more lines with the same name followed by a number in parenthesis, as in DENTAGE(1), the latter are the contrast variables corresponding to the former categorical variable. Only the contrast variables were actually included in the modelling process, since the variable on the first line is linearly dependent on the contrasts – indeed the value given for relative frequency for this baseline variable has been derived by subtracting the sum of the contrasts from unity. As an example, in the case of DENTAGE, the figure 0.18273 indicates that 18.273% of restorations were placed by dentists aged under 30. When a categorical variable has only two values (typically 0 and 1), such as ROOT, only the contrast variable is quoted in Table 4.69. A full listing of the Cox-regression analysis can be found in the appendix.

Table 4.69 Covariates entered into step-wise Cox-regression analysis

Covariate Definitions and means (relative frequencies for contrast variables)			
Covariate Name	**Description**	**Mean (relative frequency for contrast variables)**	* **= included in model O= Not included in model**
PATAGE	**Patient age (single years)**	43.76713	*
DENTAGE	**Dentist age (grouped years, under 30 = 0)**	0.18273	*
DENTAGE(1)	**Dentist age 30 to 39**	0.35227	*
DENTAGE(2)	**Dentist age 40 to 49**	0.27920	*
DENTAGE(3)	**Dentist age 50 or older**	0.18580	*
MEANANNF	**Mean annual gross fees**	65.26769	*
MEDINT	**Median interval between courses (days)**	230.98143	*
MAINTRT	**Main Treatment (Single surface amalgam = 0)**	0.14888	*
MAINTRT(1)	**Two surface amalgam, not MO or DO**	0.03396	*
MAINTRT(2)	**MO or DO amalgam**	0.30112	*
MAINTRT(3)	**MOD amalgam**	0.12868	*
MAINTRT(4)	**Composite resin**	0.25750	*
MAINTRT(5)	**Glass ionomer**	0.12986	*
TOOTH	**Tooth position (Position 1 = 0)**	0.08342	*
TOOTH(1)	**Position 2**	0.07527	*
TOOTH(2)	**Position 3**	0.09143	*
TOOTH(3)	**Position 4**	0.12254	*
TOOTH(4)	**Position 5**	0.14737	*
TOOTH(5)	**Position 6**	0.21690	*
TOOTH(6)	**Position 7**	0.19818	*
TOOTH(7)	**Position 8**	0.06489	*
CHGEPAY	**Charge-paying Status**	0.70103	*
CHPAYGR	**Change of charge-paying status (no change = 0)**	0.73315	*
CHPAYGR(1)	**non-paying to paying**	0.16646	*
CHPAYGR(2)	**paying to non-paying**	0.10039	*
CHDENTGR	**Change of dentist (no change = 0)**	0.66697	*
ROOT	**Root treatment on same tooth**	0.04322	*
ADDIT	**Additional treatment on same filling**	0.04578	*
GLASSION	**Glass Ionomer on same tooth**	0.13541	*

PINSCREW	Pin or Screw on same tooth	0.06854	*
COMP	Composite Resin on same tooth	0.26177	*
AMALGAM	Amalgam on same tooth	0.61265	O
VENEER	Porcelain Veneer on same tooth	0.00027	*
INLAY	Inlay on same tooth	0.00006	O
YEARPLAC	Year of restoration placement	1995.19617	*
QUADRANT	Mouth quadrant (Lower Left = 0)	0.21386	*
QUADRANT(1)	Lower Right	0.20945	*
QUADRANT(2)	Upper Left	0.29167	*
QUADRANT(3)	Upper Right	0.28502	*
DENTSEX	Sex of Dentist (Male=0)	0.21379	*
REGION	Region (London = 0)	0.15757	*
REGION(1)	South	0.19012	*
REGION(2)	Central	0.33661	*
REGION(3)	North	0.24672	*
REGION(4)	Wales	0.06898	*
FLUORIDE	Fluoridation Status (no fluoride = 0)	0.28247	O
COUNQUAL	Country of Dentist Qualification (England=0)	0.75439	*
COUNQUAL(1)	Other UK	0.12223	*
COUNQUAL(2)	Other Europe	0.05830	*
COUNQUAL(3)	Outside Europe	0.04740	*
COUNQUAL(4)	Other	0.01768	*
AEXAM	associated exam (None=0)	0.83055	*
ARADS	associated radiographs (None=0)	0.43258	*
APERIO	associated periodontal treatment (None=0)	0.68882	*
AAMALGAM	associated amalgam (None=0)	0.74460	*
ACOMP	associated composite resin (None=0)	0.38364	O
AGLASSIO	associated glass ionomer (None=0)	0.19496	*
AROOT	associated root treatment (None=0)	0.11154	O
AVENEER	associated porcelain veneer (None=0)	0.00304	*
AINLAY	associated inlay (None=0)	0.00285	*
ACROWN	associated crown (None=0)	0.09229	*
ABRIDGE	associated bridge (None=0)	0.00963	*
AEXTRACT	associated extraction (None=0)	0.09477	*
ADENTURE	associated denture (None=0)	0.04879	*
ASEDATIO	associated sedation or GA (None=0)	0.00888	O
ADOMVIS	associated domiciliary visit (None=0)	0.00056	O
ARECATT	associated recalled attendance (None=0)	0.00369	O
PATSEX	patient sex (Male=0)	0.53282	*

The analysis took just over 164 hours to establish 32 out of the 40 candidate categorical variables as appropriate for inclusion in the model. One of the original variables, AAMALGAM, was in fact already defined as a linear combination of the MAINTRT contrasts, because of the priority given to amalgam restorations over composite resin and glass ionomer (AAMALGAM = 1- MAINTRT(4) – MAINTRT(5). The step regression process correctly detected this.

Table 4.70 presents in detail the estimates of the Cox-regression parameters, including standard errors, significance levels, and a 95% confidence interval for the resulting constants of proportionality (Exp(B)). The Wald statistic has been used to determine the significance of each covariate. Where contrasts are involved the criterion is whether the group of contrasts is significant as a whole, even if some of the contrasts are not significantly different from the reference variable.

Table 4.70 Cox-regression parameter estimates

Cox Regression Parameters estimated for proportional hazards model								
Covariate	**B**	**SE**	**Wald**	**df**	**Sig.**	**Exp(B)**	**95.0% CI for Exp(B)**	
							Lower	**Upper**
PATAGE	0.009	0.000	1,751.91	1	0	1.009	1.009	1.010
DENTAGE			261.27	3	0			
DENTAGE(1)	0.009	0.009	1.18	1	0.278	1.009	0.992	1.027
DENTAGE(2)	0.094	0.009	103.53	1	0	1.099	1.079	1.119
DENTAGE(3)	0.118	0.010	136.23	1	0	1.125	1.103	1.147
MEANANNF	0.003	0.000	10,278.02	1	0	1.003	1.003	1.003
MEDINT	-0.001	0.000	1,528.03	1	0	0.999	0.999	0.999
MAINTRT			459.90	5	0			
MAINTRT(1)	0.218	0.018	149.52	1	0	1.244	1.201	1.288
MAINTRT(2)	0.166	0.010	266.27	1	0	1.180	1.157	1.204
MAINTRT(3)	0.244	0.012	402.14	1	0	1.276	1.246	1.307
MAINTRT(4)	-0.010	0.044	0.05	1	0.817	0.990	0.908	1.079
MAINTRT(5)	0.137	0.038	13.07	1	0	1.147	1.065	1.235
TOOTH			1,168.77	7	0			
TOOTH(1)	-0.027	0.014	3.74	1	0.053	0.974	0.947	1.000

TOOTH(2)	-0.072	0.013	28.82	1	0	0.930	0.906	0.955
TOOTH(3)	-0.119	0.014	69.44	1	0	0.888	0.863	0.913
TOOTH(4)	-0.019	0.015	1.65	1	0.199	0.982	0.954	1.010
TOOTH(5)	0.157	0.014	119.87	1	0	1.170	1.137	1.203
TOOTH(6)	0.050	0.015	11.65	1	0.001	1.052	1.022	1.083
TOOTH(7)	-0.229	0.019	151.88	1	0	0.795	0.767	0.825
CHGEPAY	-0.236	0.009	648.21	1	0	0.790	0.776	0.804
CHPAYGR			279.37	2	0			
CHPAYGR(1)	-0.104	0.011	97.36	1	0	0.901	0.883	0.920
CHPAYGR(2)	0.130	0.010	172.93	1	0	1.139	1.117	1.161
CHDENTGR	0.042	0.007	38.00	1	0	1.043	1.029	1.057
ROOT	0.400	0.014	857.71	1	0	1.492	1.453	1.533
ADDIT	0.217	0.014	232.50	1	0	1.242	1.208	1.277
GLASSION	0.198	0.037	28.19	1	0	1.219	1.133	1.311
PINSCREW	0.079	0.012	47.23	1	0	1.083	1.058	1.108
COMP	0.258	0.043	36.75	1	0	1.294	1.191	1.407
VENEER	0.460	0.168	7.53	1	0.006	1.585	1.140	2.201
YEARPLAC	0.007	0.001	25.65	1	0	1.007	1.004	1.009
QUADRANT			42.07	3	0			
QUADRANT(1)	-0.004	0.009	0.25	1	0.621	0.996	0.978	1.013
QUADRANT(2)	0.041	0.008	24.31	1	0	1.042	1.025	1.059
QUADRANT(3)	0.030	0.008	13.11	1	0	1.031	1.014	1.048
DENTSEX	0.028	0.007	13.73	1	0	1.028	1.013	1.043
REGION			111.52	4	0			
REGION(1)	-0.068	0.010	46.00	1	0	0.934	0.916	0.953
REGION(2)	-0.090	0.009	98.38	1	0	0.914	0.897	0.930
REGION(3)	-0.053	0.010	29.28	1	0	0.949	0.931	0.967
REGION(4)	-0.099	0.014	49.73	1	0	0.906	0.881	0.931
COUNQUAL			53.98	4	0			
COUNQUAL(1)	0.004	0.009	0.15	1	0.695	1.004	0.986	1.022
COUNQUAL(2)	0.025	0.013	3.87	1	0.049	1.026	1.000	1.052
COUNQUAL(3)	-0.099	0.015	45.02	1	0	0.906	0.880	0.932
COUNQUAL(4)	-0.034	0.022	2.50	1	0.114	0.966	0.926	1.008
AEXAM	-0.148	0.009	300.29	1	0	0.862	0.848	0.877
ARADS	-0.120	0.007	309.82	1	0	0.887	0.875	0.899
APERIO	-0.171	0.007	578.55	1	0	0.843	0.831	0.854
AAMALGAM	-0.040	0.010	16.73	1	0	0.960	0.942	0.979
AGLASSIO	0.064	0.012	27.29	1	0	1.066	1.041	1.091
AVENEER	-0.375	0.061	37.76	1	0	0.687	0.610	0.774
AINLAY	-0.248	0.060	17.06	1	0	0.780	0.694	0.878
ACROWN	-0.021	0.010	4.35	1	0.037	0.979	0.959	0.999
ABRIDGE	-0.200	0.030	43.51	1	0	0.819	0.771	0.869
AEXTRACT	0.043	0.010	16.84	1	0	1.043	1.022	1.065
ADENTURE	0.055	0.013	18.06	1	0	1.057	1.030	1.084
PATSEX	-0.089	0.006	224.17	1	0	0.915	0.905	0.926

Apart from some of the individual contrasts, most of the covariates were statistically highly significant. In interpreting the coefficients, it should be noted that Exp(B) greater than one suggests increased hazard, while Exp(B) less than one indicates a reduction in hazard, as compared with the appropriate reference category. For example, compared with dentists qualified in England, other UK qualified dentists (COUNQUAL(1), 1.004) have 0.4% greater estimated hazard of re-intervention within a specified time period, and those from overseas, excluding Europe (COUNQUAL(3), 0.906), have 9.4% lower estimated hazard. But note that the 0.4% figure for other UK qualified dentists is not significant, and indeed the confidence interval comfortably includes unity.

To get some idea of the priority with which these elements of the model should be considered, Table 4.71 shows the order in which the variables were added to the model. The fuller description of the variables in Table 4.69 should be referred to when reading this table. Note also that 'associated' refers to treatments carried out on the same course of treatment, but not the same tooth, as that in which the restoration was placed.

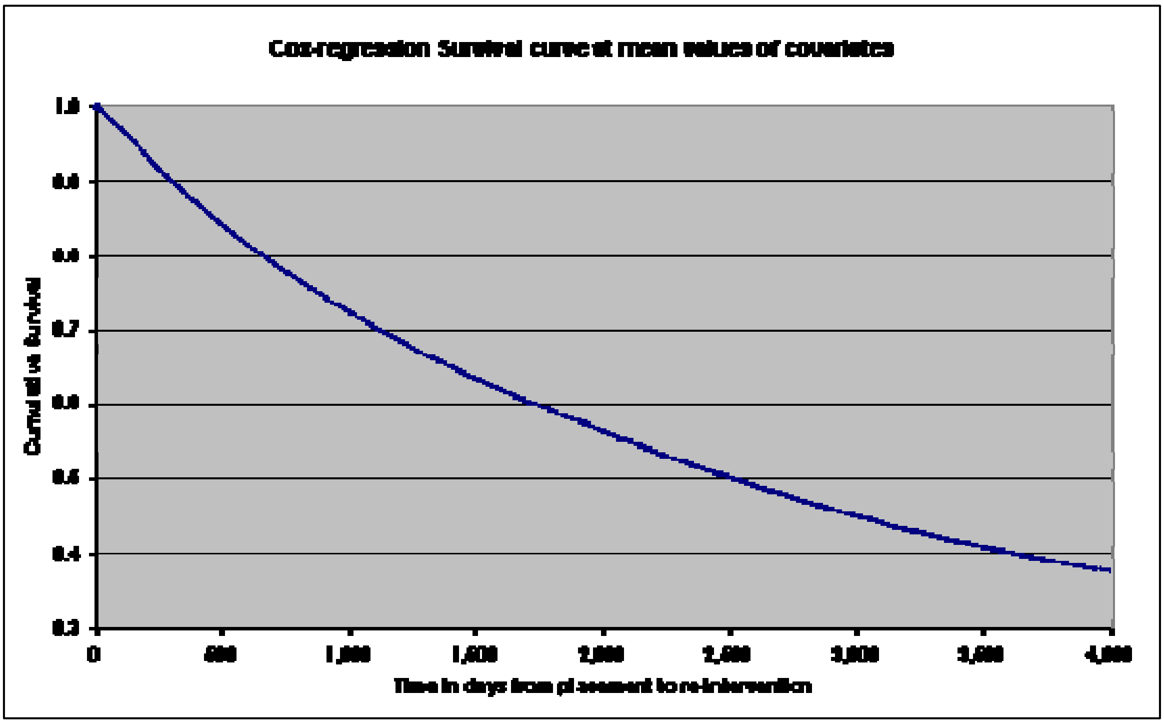
Table 4.71 Order in which covariates were added to the Cox-regression model

Step	Covariate
1	PATAGE
2	MEANANNF
3	MEDINT
4	TOOTH
5	AEXAM
6	MAINTRT
7	ROOT
8	APERIO
9	CHGEPAY
10	ARADS
11	CHPAYGR
12	ADDIT
13	PATSEX
14	DENTAGE
15	REGION
16	GLASSION
17	ABRIDGE
18	PINSCREW
19	COUNQUAL
20	COMP
21	AVENEER
22	CHDENTGR
23	QUADRANT
24	YEARPLAC
25	ADENTURE
26	AGLASSIO
27	AINLAY
28	AEXTRACT
29	AAMALGAM
30	DENTSEX
31	VENEER
32	ACROWN

4.4.4 Modelling the Base Hazard Function

Figure 4.73 shows the cumulative survival curve using the Cox-regression estimated hazard ratios evaluated at the mean of the covariates. The curve has the same shape, including the early inflexions, as the Kaplan-Meier empirical survival curves (section 4.3.3.2 and Table 4.68).

Figure 4.73 Cox-regression base survival curve

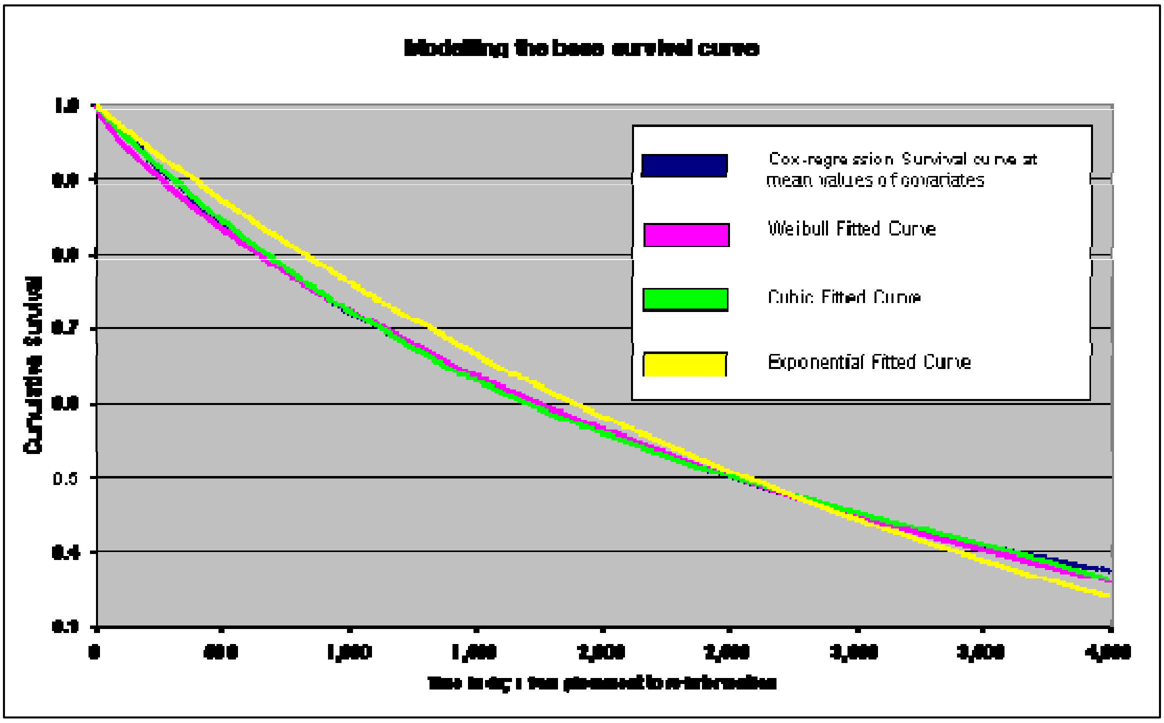


The simplest model for a hazard function is a constant, and the associated cumulative survival function is an exponential. Figure 4.74 illustrates the extent to which such a function can be made to fit the Cox-regression base survival curve. In this case the exponential function has the form y=exp(-0.0003t).

A better fit can be obtained by using a Weibull function, fitting the curve using a non-linear regression algorithm – details can be found in the appendix. This is also illustrated in Figure 4.74. The fitted cumulative survival function has the form $y= \exp(-0.001007584t^{0.833991774})$.

An even better fit has been obtained using a cubic survival function. In this case the underlying hazard function is a quadratic, which not only reduces in the early part of the life of the restoration, but also will eventually increase again – the ‘bathtub’ shape. For the cubic shown in Figure 4.74 the equation is $y=(-8E-12)t^3+ (8E-08)t^2-0.0003t+1$.

Figure 4.74 Modelling the base hazard function



5 DISCUSSION

5.1 Research Methods

The database on which this research has been conducted is the largest and most comprehensive set of records of dental treatment available anywhere in the world. By comparison with other studies, conventional absolute statistical significance is almost irrelevant, since the sheer volume of cases is such that any finding which is clinically significant is also statistically significant.

However, it is important to recognise that this work is essentially observational rather than experimental. Although the study enables the quantification of the survival curves of directly placed restorations in a variety of circumstances within the General Dental Services, there is no element of control of these circumstances, nor any element of randomising the patients or the treatments which they receive. Thus while the one-year re-intervention rate for single-surface amalgam restorations on patients aged 35 may be accurately measured at 5.0% (Table 4.21), this reflects the circumstances and teeth in which such restorations were, in practice, placed by GDS dental surgeons over the time period covered.

What cannot be inferred directly from this study is whether, under controlled conditions, one type of directly placed restoration would perform better than another. Certainly, some of the circumstances can be controlled, such as the age and sex of the patient, the position of the tooth, or the charge-paying status of the patient (which may itself act as a proxy for other factors such as diet and oral health). The possibility nevertheless remains that GDS dentists (or even dentists in general) will choose to use one type of filling rather than another according to dental or other factors which are not recorded in the GDS payment claim.

It is however arguable that what is being measured in this study is precisely what the various stakeholders in the GDS wish to know, even if the findings might spark a new set of randomised controlled trials to explore the observational results further. It may indeed be that certain materials, such as glass ionomer, are generally used in circumstances where another material, such as dental amalgam, would be unsuitable. Aesthetic considerations on anterior teeth could be a relevant factor, for example. The absolute measurement of survival rates still remains highly relevant to both patient and co-payer, and indeed to the dentist providing the treatment.

Although the whole of this research is based on GDS data from the DPB, there were three distinct but complementary measurement exercises, each with its own methodology and rationale. The findings are discussed in some detail in the following sections, but it is as well to have an overview of the strategy.

The early life analysis is conceptually a very straightforward exercise. By restricting the timescale to a one-year horizon with a one-month start period, issues of censoring and change over time have effectively been sidestepped. The only censoring taken into account is that at the end of the time period. Because the whole of the GDS population of treatment activity was available the opportunity was taken to take account of the age of the patients, so ensuring a more homogeneous sample population. From the early life analysis important lessons can be learned about the materials and methods in current use, and in particular, the method can give rapid warning of circumstances where early catastrophic failure (resulting in the loss of the tooth) may be prevalent.

The cross-sectional analysis was born of a recognition that the existing literature appeared not to have fully exploited the information potentially available to the practising clinician. The analyses in this thesis demonstrate the equivalence of four different methods of analysing restoration activity data, but among those methods there is one, the Nelson-Aalen estimator, which combines information on both restorations *in situ* and those where the restored tooth receives a further intervention, and which does not rely on any additional data about teeth other than those which the dentist is examining anyway at the time of cross-section. Cross-sectional analysis has the added advantage for the clinician that the patient is necessarily available for examination and interrogation, so that additional information can be used to interpret the bald statistical outcome measures. This methodology is proposed as a tool with which dentists may conduct their own clinical audits and peer reviews.

The full eleven year analysis tackles some formidable statistical issues, particularly those concerned with censoring. Since the data describe patterns of attendance, without any explicit record of non-attendance, a method had to found to extend conventional Kaplan-Meier analysis to cope with imputation of the time when and the probability that a patient may cease to be available for treatment under the GDS. As with the other two exercises, statistical significance is not a problem, but in the case of the eleven year data the important issue is rather the development of appropriate measures to ensure unbiased estimates.

It is in the nature of a block of sequential attendance records that there has been greater follow-up time for earlier records than for more recent ones. Such is the case with the DPB dataset. Courses of treatment which were completed in January 1991 have had more than eleven years of potential follow-up, while those completed in December 2001 have only a few days left within the observation period. Clearly ‘not seen again’ is inadequate on its own as a criterion for deciding whether to treat a case as censored. The longer the period of follow-up, the greater the opportunity for a patient with large re-attendance intervals to re-appear in the records, and thus to confirm his or her presence in the at risk population throughout the intervening period.

One partial solution to this dilemma is to restrict the analysis to patients whose minimum attendance interval is below some specified time limit, or at least to ignore evidence of re-attendance after that time. This would at least provide a consistent basis for combining data from different parts of the historical record. The cost though is a trade-off against obtaining information about infrequent attendees – or those with gaps in their records. If patients who attend irregularly have poorer oral health than regular attendees, and oral health is associated with longevity of restorations, then omitting these patients could lead to biased overall conclusions about longevity.

Another option is to look only at the early life of restorations, so that no restoration is tracked for more than, say, one year. This again provides a consistent basis for comparisons between groups of patients and types of treatment, but at the cost of jettisoning valuable if biased information about the long-term performance of different types of restoration.

Rather than compromising by adopting one of these partial solutions, the method developed in section 3.4 was adopted. This method of estimating probability of eventual re-attendance, while providing an acceptable approximation for the purpose of adjusting the Kaplan-Meier procedure, suffers from a systematic bias since it uses the observed number of re-attenders, rather than the expected number of re-attenders. The analysis in section 4.3.2 provides evidence that, for this eleven-year dataset, the bias is small. However, a recursive extension of the method in section 3.4.1 could be used to overcome this drawback. The method can be summarised as follows, using the terminology of section 3.4.1:

Let E_i be the expected eventual number of re-attenders which have been observed for i months (to re-intervention or until March 2002). Successive values of E_i involve overlapping counts of patients. Let P(i) be the probability that a patient observed without re-attendance for i months will eventually re-attend. Then

P(i) can be better estimated as $P(i) = \dfrac{E_i}{\sum_{j=i+1}^{M}(N_j + R_j)}$ ……………..……………(i)

E_i satisfies the following recurrence relation:

$$E_i = \sum_{j=i+1}^{M} R_j + \sum_{j=i+1}^{M} P(j) N_j \quad \text{………………………………………………………….(ii)}$$

Furthermore, because non-attendance for M months is regarded as indicative of eventual non-attendance,

$$E_M = 0 \quad \text{…………………………………………………...................……………(iii)}$$

Equations (i), (ii) and (iii) can now be used recursively to calculate E_i and P(i) for all values of i from M down to 0.

Given that a case has been censored, it is still necessary to decide when it was censored. Except for cases censored at the end of the observation period, there is an interval, from the date of the last visit to the end of the observation period, within which the patient is presumed to have ceased to be ‘at risk’. There are many possible options for choosing a time within this interval, and the choice between them may most properly be informed by an external knowledge of patterns of patient behaviour, rather than any patterns in the observed data.

The two extreme options are to assume censoring on the date of last visit or to censor only at the end of the observation period. A compromise would be half-way between the two. A more realistic option would be to allow an interval after the date of last visit. In principle, this interval could be dependent on various characteristics of the patient, but a pragmatic choice, informed by the analysis in section 4.3.2, is a fixed interval of one year – the period within which the NHS agrees to underwrite a free replacement of a restoration.

With the eleven year data the shape of the survival curve starts to become important, as does the relationship between explanatory factors and the curve. Plots of log cumulative hazard against log time indicated that most of the important hazard factors had a proportional effect on the hazard, so a Cox regression model could be developed to give an intuitive interpretation of the risk factors, in terms which might make sense to clinicians and patients. Finally, alternative curves can be fitted to the base hazard function derived from a Cox regression model, from which it is possible to make rationally based extrapolations of the data to predict the longer-term survival of restorations.

5.2 Early Life

5.2.1 Patients Born in 1965

Initially, the early life analysis was limited to restorations on first molar teeth on patients born in 1965. These patients were aged about 35 years and may be expected to have had a relatively complete dentition. They also experienced a large volume of restoration activity. First molar teeth have the highest number of restorations, and there are sufficient numbers of each of the six distinguishable types of direct restoration for valid comparisons between them to be drawn. Discussion of some of these early results can be found in articles written by the author on the website of the DPB (www.dpb.nhs.uk). The tables in chapter 4 and the appendix provide a comprehensive reference source, from which the following observations can be gleaned.

5.2.1.1 Early re-intervention rates on first molars ranged from about 6-8% for single surface amalgams and non MO/DO two surface amalgams to about 15-18% for glass ionomer and composite resin.

This demonstrates that the material used for restoration may be a good indicator of the likelihood of early re-intervention.

5.2.1.2 For MO, DO, and MOD amalgam fillings the rate was around 11-12%.

This indicates an unsurprising relationship between cavity size and likelihood of re-intervention. The larger the restoration, the more likely that early re-intervention will occur.

5.2.1.3 About a third of the re-interventions were of the same type as the original, a quarter were other fillings, about 10% were extractions, about 10% were crowns, and another 10% were multiple treatments.

A possible interpretation of this finding is that in more than half the cases of early re-intervention, the treatment plan has been changed in the light of the perceived need for re-intervention. This is borne out by the relatively small proportion of re-interventions which were the subject of claims for payment under guarantee (section 4.1.5).

5.2.1.4 A plot of log cumulative hazard against log of time for different materials gives approximately parallel straight lines, with a slope near to 45 degrees, implying that a proportional hazards model, with an underlying exponential survival function, may be appropriate, at least for modelling the first year of survival behaviour for first molars.

An exponential model implies a constant hazard – in other words, there is no suggestion of a systematically higher or lower probability of re-intervention according to the time since the placing of the restoration. This overall finding should however be tempered by the following observation.

5.2.1.5 There was some grouping of the re-interventions around six months, suggesting that the six-month examination interval may act as a trigger for re-intervention.

However, only a relatively small proportion of the cases are affected by this feature, which suggests that most of the re-interventions occurred at the instigation of the patient. Even in the case of a six-monthly examination, the patient may ‘save up’ his or her concerns about the need for re-intervention until the pre-arranged check-up visit to the dentist.

5.2.1.6 There were differences between the quadrants of the mouth, but they were small compared with the differences between restoration materials and sizes of amalgam fillings.

This is a good example of where statistical significance should be subordinated to clinical significance. It appears from these findings that the undoubted differences in technique required for restoring upper and lower teeth, and teeth on the right and the left side of the mouth, do not result in any serious variation in the early re-intervention rates. Similar considerations apply to the physiological and mechanical differences between upper and lower jaws, and the extent to which these may differ between left and right – for example, whether a right-handed patient brushes his or her teeth equally efficiently on the right side and on the left.

5.2.1.7 For first molars, the expected treatment rate, by following untreated first molars, was about three per cent.

In comparison with other studies, and indeed in interpreting these results, it is important to gain some idea of what the likely outcome would be for the tooth if restoration had neither been proposed nor carried out. There will always be some cases where unrelated circumstances will give rise to a need for re-intervention, and it would be unreasonable to attribute the cause for all subsequent interventions to the original restoration alone. Nevertheless, what this three per cent figure demonstrates is that the placing of the restoration, accompanied as it is by an assessment of all the needs that the tooth has for treatment at the time, does not achieve anything near restoration to the level of early life expectancy enjoyed by the other teeth in similar positions in the same mouth. Clearly, this statement relies on the assumption that most patients with one restored first molar teeth have three other first molar teeth still present in their mouths for comparison, but for thirty-five year old patients in the year 2000, the assumption seems reasonable.

Having addressed the pattern for first molars, the patterns for other teeth were considered. Further commentary can be found in Lucarotti et al (2002a).

5.2.1.8 The results relating to re-intervention were similar for second molars, with single surface amalgam at 4%, MO/DO and MOD at 10-12%, glass ionomer and composite resin at 12-17%.

5.2.1.9 On second molars the increased hazard at 6 months was very pronounced for glass ionomer and composite resin, suggesting these two materials may fail in a way which does not attract the concern of the patient.

This difference between materials may be related to the circumstances in which tooth-coloured materials are permitted to be used on posterior teeth, namely on non-occlusal surfaces only. Failure of a restoration in such a location is unlikely to be as functionally important to a patient as a restoration in an occlusal cavity, although a cervical lesion can give rise to symptoms of sensitivity. Glass-ionomer Class V restorations may require very little excavation of the tooth material, and the loss of such a restoration may be detectable only by the dentist.

5.2.1.10 For second molars the figures for the four quadrants were again similar, but the lowest re-intervention rate was again on the upper right quadrant.

5.2.1.11 When all eight tooth positions are combined, single surface amalgams, at about 5% re-intervention rate, were still clearly associated with the longest survival time, and the order of the other materials was similar to that for 1st molars, ending with glass ionomer at about 13%. However, the re-intervention rates for composite resin and MOD amalgam were almost indistinguishable at around 11%.

5.2.1.12 For incisors, the treatment of choice was generally composite resin, and this had a re-intervention rate of 10-11% in the first year.

5.2.1.13 For other restoration materials on incisors (primarily glass ionomer) the re-intervention rate was similar - 10-11%.

5.2.1.14 For canines the re-intervention rate was better - about 9% for composite resin (the material of choice), and about 5% for glass ionomer.

5.2.1.15 When third molars were restored, their re-intervention rate was lower, at about 6%, than for any other tooth position.

5.2.1.16 When an incisal angle was involved in the restoration of an incisor, there was an additional hazard, which was more severe if both incisal angles were involved. The re-intervention rate in such cases rose from 10% to 14-18%. Such treatments invariably used composite resin as a restoration material.

5.2.1.17 Similarly, other additional treatments, such as dentine pins, cusp tip restoration and other fillings on the same tooth, all gave rise to generally higher hazards of re-intervention.

5.2.1.18 Control analyses for next treatment on teeth which were not treated in March 2000 confirmed that on all teeth the rate was below 4%.

This suggests that a restored tooth has a shorter expected interval to next intervention than any tooth in the same tooth position (but different quadrant) in the same patient. Although the selection of the tooth for treatment implies that its condition was poorer than that of its untreated neighbours, this control analysis implies that the restoration is insufficient to reverse the relative status of the tooth.

5.2.1.19 The association between the quadrant and tooth position, within the 4%, was interesting, with lower incisors and canines having fewer treatments (1-2%) compared with those in the upper jaw (3%). On molars and premolars there was little difference.

5.2.1.20 There was a clear association between the sex of a patient and the likelihood of re-intervention within a year, averaging about two percentage points higher re-intervention for females compared with males. This was consistent across different restoration types and mouth quadrants.

A possible explanation may relate to cultural differences in attitudes between males and females. Aesthetic considerations may be more important to females, who may not be as easily satisfied with the early performance of a restoration as males. Females may also act more promptly to report such early problems to their dentists.

5.2.1.21 Although even charge-paying patients have a guarantee of free replacement within a year, there is still a significantly higher rate – more than one percentage point – of re-intervention on patients who do not have to pay charges.

There are several possible explanations for this. Patients who have to pay for the initial restoration may be more wary of a treatment plan where there is more risk of early failure. For example, such a patient might prefer to opt immediately for an extraction rather than a risky attempt at saving a heavily restored tooth, knowing that at least he or she will avoid having to pay for ineffective restoration work. A dentist may also wish to avoid his patient becoming aggrieved at having to pay for such work. Another possibility is that the standard of diet and oral hygiene of patients who do not have to pay charges may be poorer than that for charge-payers, resulting in a greater likelihood of early deterioration of the restoration. It is also possible that these and other considerations may influence the clinician in the choice of recommended treatment plan.

5.2.1.22 The overall patterns for patients who paid charges (Figure 4.2) and for those who had retreatment under guarantee (Figure 4.3) are similar, except that glass ionomer and composite resin are reversed.

This may be attributable to the higher proportion of composite resin restoration for which the re-intervention is of the same type – the guarantee is restricted to ‘like for like’ replacement treatment.

5.2.1.23 About 20% of patients whose restored tooth was retreated within one year had the re-intervention carried out by a dentist other than the one who placed the original restoration.

By the nature of the early life analysis, it is not practicable to determine directly whether the likelihood of early re-intervention is related to whether or not the patient attends a different dentist, since the attending of a different dentist within one year is itself likely to be related to the patient’s perceived need for re-intervention.

5.2.2 Extension to Other Patient Age Groups

The charts in section 4.1.7 provide an overview of the association between patient age and the early life of dental restorations. From both (Figure 4.5 and Figure 4.6) it is clear that the older the patient, the more likely that a restored tooth will receive a re-intervention within one year. The difference is dramatic – ranging from around 5% for 25-year-olds to over 15% for those aged 65.

At least two factors contribute to the effect of patient age. Firstly, the patients of different ages come from different cohorts. A patient aged 35 in 2000 has had a different treatment history in his or her first thirty-five years compared with a patient aged 65 in 2000, whose first thirty-five years ended in 1970, when treatment philosophies and patient expectations were very different. The second factor is an intrinsic one. A tooth in a 65 year-old has had more exposure to the physical, chemical and biological agents which lead to decay and fracture than one in a 35-year old. A restoration placed in such a patient is arguably reliant on a less secure base than in a younger patient. Against this it might be argued that the more vulnerable teeth may have already been lost from the 65 year-old mouth, leaving only the more decay resistant teeth. However, the evidence from the decennial Adult Dental Health Survey (Office for National Statistics, 2000, Tables 3.1.27 to 3.1.31) suggests that there is a gradual progression for all teeth from their virgin state through increasingly more extensive restorations to eventual extraction, so that any patient who already has lost teeth to extraction (except for orthodontic reasons), is likely to have some teeth that are nearly bad enough to be extracted.

The expectation would then be that the older the patient, the larger the fillings, and the greater the likelihood of early re-intervention, particularly by extraction. From Table 4.35 and Figure 4.6 it can be seen that this is broadly true – certainly there is a clear rise in the proportion, both relatively and absolutely, for which extraction is the type of re-intervention, as patient age increases. There is a considerable increase in the proportion of tooth-coloured restorations, particularly composite resin. However, the balance between different types of amalgam restoration has changed relatively little, and if anything the proportion of the largest such restorations, item 1404 (MOD), has actually fallen.

This may tie in with the observation about Figure 4.5 that single surface amalgams and MOD amalgams seemed to have much closer likelihoods of early re-intervention in the older patients than in the younger. It may be that the contrast here is between ‘patching’ an already extensively restored tooth and placing a first single-surface amalgam in a virgin tooth. In the younger patient the size of restoration is indicative of the extent to which the whole tooth is damaged, whereas for the older patients the tooth may already be in a heavily restored state, irrespective of the type of restoration currently being placed.

5.3 Cross-sectional Inference

Cross-sectionally based analyses have many intrinsically attractive features compared with full longitudinal studies. They are efficient in their use of data, to the extent that the data used are restricted to those cases for whom the full history to date is available. No energy is expended on retrieving records for patients who are no longer traceable. Furthermore, the records which are required for cross-sectional analysis are available for clinical reasons at the time the patient attends for the cross-sectional examination.

Unlike a prospective longitudinal study, the timescale for the production of useful results from cross-sectional studies is relatively short, determined only by the cross-sectional period. There is no requirement to recruit participants in advance, and the danger of treatment bias (where the operating dentist is influenced in choice or quality of restoration by the knowledge that the patient is included in the study) can be avoided, at least in the initial placement of the restoration.

There are particular advantages for the individual practitioner, in that a cross-sectional study provides information about restoration longevity on those patients of greatest concern to his/her practice – the regular patients. Furthermore, not only can standard rates be calculated for intervals to re-intervention, for comparison with national and local rates published by such bodies as the DPB, but the dentist can interpret the standard rates by adding locally collected data derived from interviewing and examining the patient at the time of re-intervention. This may provide vital insight into the specific circumstances which give rise to re-interventions, and the extent to which improvements in the original restoration or subsequent maintenance might extend the interval to re-intervention.

The empirical test of the cross-sectional theory (Section 4.2) is self-contained as a demonstration of the extent to which the three cross-sectional inference methods match a full conventional Kaplan-Meier analysis for the same period. However, it is also useful to compare the Kaplan-Meier analysis for claims with dates of acceptance in the period March 2000 to April 2001 (Figure 4.7) with the corresponding analysis restricted to claims scheduled in March 2000 (Figure 4.1). There are very few cases in common between the two datasets, yet the charts are almost indistinguishable. This in itself could be considered to be an eloquent testimony to the robustness of the data provided on activity in the General Dental Services.

Returning to the comparison within the cross-sectional dataset, it can be seen that the Kaplan-Meier chart (Figure 4.7) is smoother than the other charts. This reflects the much greater volume of data used. In particular, all restorations which had re-interventions before April 2001 are necessarily excluded from the cross-sectional analyses, except as a component of the volume of historical placement of restorations.

The chart based on re-interventions alone (Figure 4.8) uses the known historical rates of placement of restorations, as well as the re-interventions carried out in the cross-sectional period (April 2001). However, such historical placement volume data are not generally readily available to clinicians, so using re-interventions alone is likely to be an unreliable or impractical proposition in most dental surgeries.

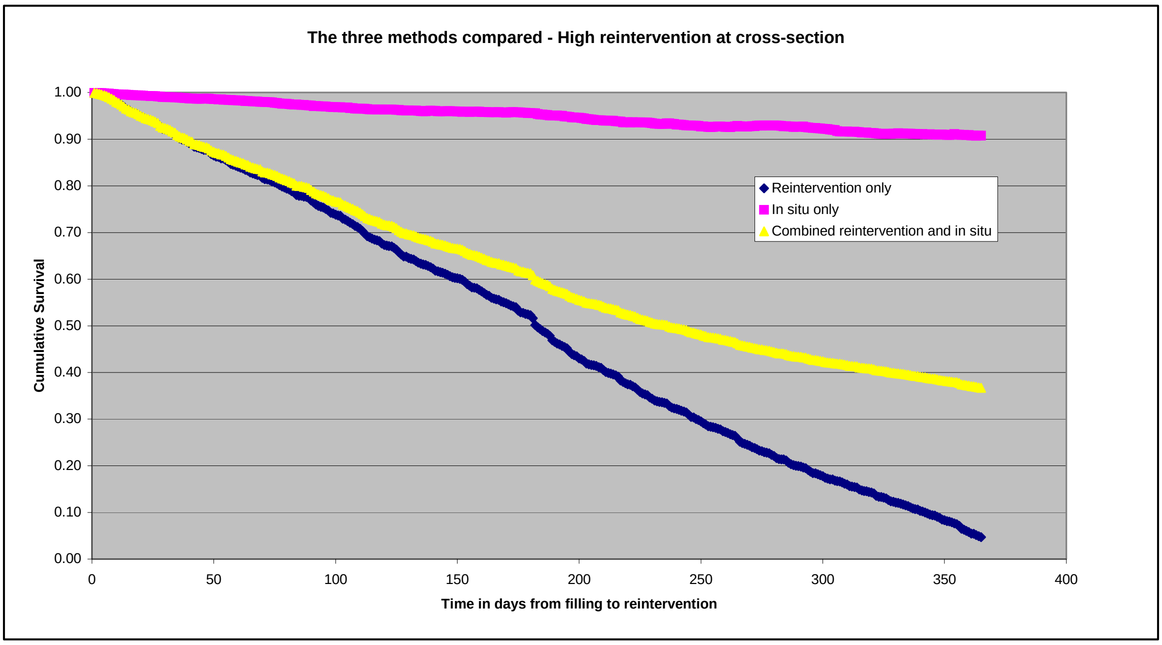
The curves derived solely from restorations *in situ* (Figure 4.8) estimate the survivor functions directly, and the deviations from monotonicity reflect both sampling variation and seasonal variation. This chart makes explicit the intrinsic feature of cross-sectional analysis that the time to re-intervention is confounded with the date of intervention. For example in any analysis of the April 2001 cross section all estimates of re-interventions after six months are based on restorations placed in October 2000. As with the analysis based on re-interventions alone, the analysis based on restorations *in situ* also requires historical data about the rate of placement of restorations, so this method is unlikely to be very practicable for surgery use.

The final, Nelson-Aalen, method (Figure 4.10) combines the benefits of both the previous methods and avoids the need for historical data on placement volumes. In effect, the restorations *in situ* act as a built-in record of previous levels of restoration placement. There are of course close similarities between Figure 4.10 and Figure 4.8, since both have ‘steps’ at the same time intervals (when restorations were re-intervened upon in April 2001).

The agreement between the three methods and Kaplan-Meier is so close that it is tempting to infer that this agreement is inevitable and trivial. The differences in fact represent a measure of the departure, if any, from the underlying assumption of any survival analysis, namely that the group of cases for which a survival curve is drawn come from a population with the same survival density function. In particular, it is important that the survival expectancy should not be related to the date of placement or the date of re-intervention.

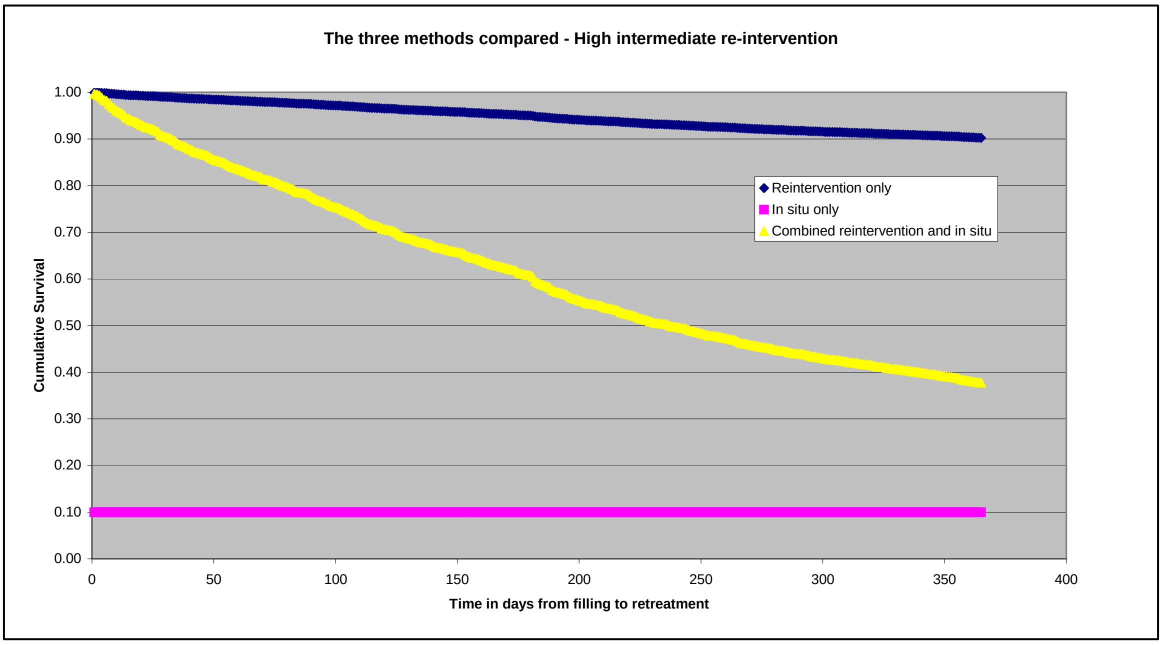
If we replace some of the observed data by hypothetical data which break the above assumption it is possible to recreate one of the estimated curves while grossly distorting the others.

Figure 5.1 Simulation of high re-intervention at cross-section



The first simulation (Figure 5.1) increases the number with re-intervention at the cross-section time t (April 2001) ten-fold, up to the maximum possible given the number surviving to time t. There is thus a strong correlation between the time when the restoration was placed and the shape of the underlying survival curve for restorations placed at that time, which has a sharp dip, corresponding to a spike in the hazard function, at time t. The curve estimated by using only in situ restorations depends only on the surviving cases in situ at (the start of) time t, and is therefore unaffected. None of the curves accurately represents a sampled population, nor would a curve based on a Kaplan-Meier analysis, since the underlying data are heterogeneous.

Figure 5.2 Simulation of high re-intervention before cross-section



The second simulation (Figure 5.2) leaves the number with re-intervention at time t unchanged, but wipes out 90% of the originally placed restorations by time t. In this case the *in situ* method gives a constant 0.1 survival function, the result of using re-intervention alone remains unchanged, and the combined method again reflects a compromise between the other two.

What both these simulations have in common is that the cross-sectional re-intervention rate is inconsistent with the restorations in situ. Conversely, the closer the three curves agree, the better we can conclude that the survival pattern is unrelated to the date at which the restoration was placed or the date when re-intervention occurred. Figure 4.11 is therefore reassuring, although it relates only to patients of a particular age, and to a particular cross-sectional time-period.

Although the assumptions of time-invariance apply both to cross-sectional and Kaplan-Meier analyses, a single cross-sectional analysis provides no opportunity to measure change over time. With Kaplan-Meier it is possible, by grouping at least the dates of placement, to test for change over time, although clearly less of the survival curve can be estimated from recent data than from the earliest. For cross-sectional data the only recourse is to repeat the exercise for different cross-sectional times, and compare results over time. Even so, cross-sectional charts are still vulnerable to systematic distortion by changes in the survivor function over time.

The point estimates on the cumulative survival curve are necessarily confounded with the times at which the restorations were placed. The estimate of cumulative survival to time *t* can be derived only from restorations placed *t* units of time prior to the time of cross-section. If indeed there is an underlying time-related change in the survival function, then this will result in a distorted picture of the survival curve. For example, an underlying linear survival curve $S(t) = 1- B_p t$, where p is the date when the filling was placed and t is the time elapsed from placement to cross-section, would appear from a cross-sectional analysis to be convex if $B_{p-1} < B_p$ (survival getting worse) for all p in the observation period, and concave if $B_p < B_{p-1}$ (survival improving). This is illustrated in Figure 5.3 and Figure 5.4, which use fictional data. In each case the apparent survival curve is constructed piecewise from segments each over a short period of placement time. Depending on the method of estimation used, these segments are joined together, possibly with monotonicity constraints. Figure 5.3 shows that as overall survival improves, leading to decreasing B_p, so the apparent survival curve has a concave distortion. Figure 5.4 shows that deteriorating survival appears as a convex distortion. A Kaplan-Meier analysis of a fuller data set would also be distorted, but the assumption of time independence could be tested by stratifying by placement time.

Figure 5.3 Distortion by improving survival

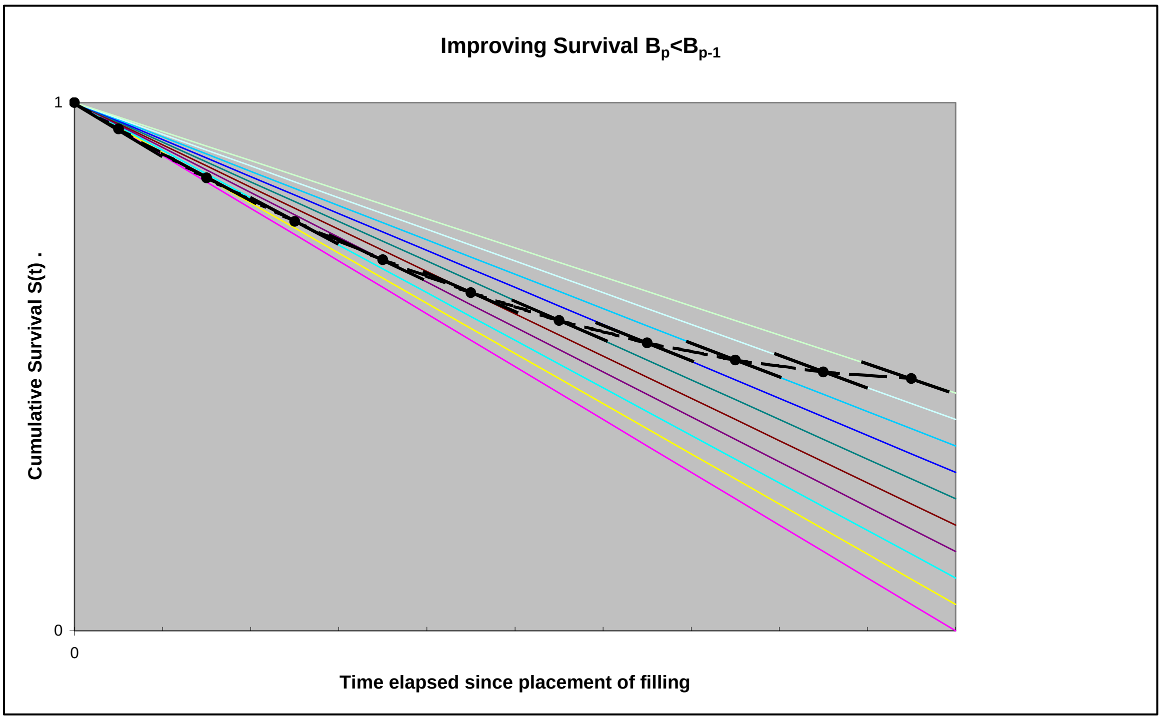
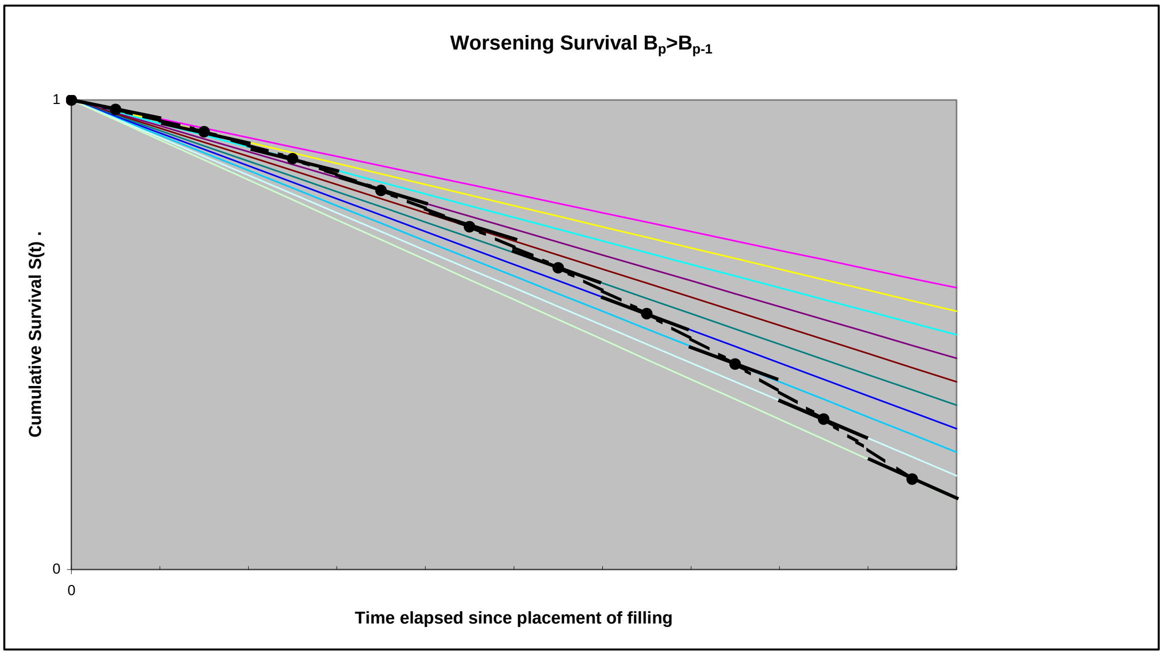


Figure 5.4 Distortion by worsening survival



Having established the theoretical and empirical basis for this method of cross-sectional analysis, it remains to consider the practical considerations faced by a dental practice in using it to measure their own clinical experience.

Definition of the population of interest is crucial. In practice, it will be necessary to confine the study to regularly attending patients, and the cross-section period should cover one round of the normal recall interval adopted by the practice (currently six months is common within the GDS). The population must be defined in advance, and all members of the population should be examined at least once during the cross-sectional period. All restorations *in situ*, provided they were placed by the practitioner (or possibly by other members of the practice, provided comprehensive records are available) must be included, not just those in patients with re-interventions.

Within the above general constraints, various measures can be used to restrict the scope of the study. The population can be restricted to particular types of restoration (eg composite resin only), or particular types of tooth (eg anterior). Alternatively, the population of patients may be restricted, either by drawing a random sample or by restricting the age range. All these measures can enable a useful piece of research to be completed within the resources available for extraction of treatment records and collation of data. A practice with existing computerised treatment records is likely to be able to perform these tasks more efficiently. The work involved is considerable, but could form part of a programme of systematic clinical audit and peer review, resulting in effective clinical governance and an increasingly evidence-based treatment philosophy.

5.4 Full Longitudinal Data

5.4.1 The Sample Context

The tables in section 4.3.1 confirm that the sample of patients is typical, in age and sex structure, of the population receiving General Dental Services. The patterns of attendance are generally plausible, though for various reasons we may expect that some patients have appeared twice, under two different patient identities (defined by surname, first initial, sex and date of birth). This arises through transcription errors, variations of spelling and choice of first name, and changes of surname on marriage or other such event. The method of analysis does however compensate for this.

On the other hand, there will have been some occasions when two patients shared the same patient identity, and in these cases the number of attendances and treatments will have been inflated. However, the effect is much diluted when the analysis is restricted to the life of restorations in individual teeth. In addition to the normal chance of two patients with a common surname happening to share the same initial, sex and date of birth, one or two examples have been found where an ethnic generic name such as 'Kaur' has been used, together with a local convention on initial and date of birth, to give the same patient identity to a whole series of individuals attending the same surgery. However, within the total volume of data analysed, such cases may be considered to have a negligible effect.

The sample of patients is stratified by age, and clustered by date of birth. There is no great reason to suppose that the date of birth within a year is closely related to the likely interval between restoration and re-intervention (as is demonstrated by Figure 4.35), and age is clearly so related (Figure 4.25). It follows that the sample of patients is likely to be more representative of the patient population than a simple random sample.

On the other hand, the restorations are clustered by patient, and it is clear from section 4.3.3.8 that there is great variation between patients in their expected intervals between restoration and re-intervention. No explicit attempt has been made to allow for the resultant loss of precision, and standard errors and significance tests should therefore be treated with caution, and regarded as indicative rather than definitive. The replication analysis (section 4.3.6) gives some confidence that the order of magnitude of the standard errors is reasonable. Alternatives could include developing a frailty or multi-level model, explicitly allowing for a frailty factor for each individual patient, or producing empirical estimates of standard errors by repeated subsampling. In this work the objective has been to use very large samples and to develop methodology to get unbiased estimates, knowing that the resulting precision would still be much higher than that for any existing studies of the subject.

The pattern of restorations by age of patient (Table 4.44) paints a picture of the transition from virgin tooth (age 18 or 19) through progressively more complex direct restoration, peaking in the age range 30 to 39, followed by indirect restoration (especially crowning) or extraction, resulting in a shrinking pool of available teeth as patients move into older age groups.

Within this pattern, the peaks for composite resin and glass ionomer occur in older patients, suggesting that anterior teeth (in which tooth-coloured materials predominate for restoration) retain their virgin status for longer than molar and premolar teeth.

5.4.2 The Overall Survival Curve

Section 4.3.3.2 describes the overall survival curve for time from restoration to next intervention on the same tooth. The estimation of this curve for directly placed restorations provided in the GDS was the primary goal of this research. The resulting empirically measured curve lies comfortably within the range estimated in the literature (section 2.6).

Not only have the percentage points and rates at one, five and ten years been quantified, with standard errors, but the curve itself has been subjected to further analysis with a view to characterising its underlying form by a parametric equation. The plot of log cumulative hazard against log time is approximately linear, which implies that a Weibull function would be a reasonable approximation. The nearness of the slope to unity suggests that an exponential, which is a member of the Weibull family, might be an adequate simple descriptor function. In this case the hazard would be constant, at around 8% per annum.

5.4.3 Treatment Type

Treatment type is clearly important. The curves in Figure 4.21 and Figure 4.22 suggest that the hazards for different types of treatment are proportional, except for tunnel restorations and root fillings without direct restorations. Tunnel restorations are rarely used anyway, and root fillings without direct restorations are heterogeneous, so that their survival in many cases reflects the characteristics of the indirect restoration, such as crown, bridge or inlay.

The survival time recorded in this work is measured by the time interval from restoration to the next intervention on the same tooth, irrespective of whether the new intervention replaces, overlaps with, or even is entirely separate from, the original restoration. It is interesting to speculate as to whether the application of 'Robinson's Rules' (described in section 2.4.1) would change the picture. Some types of restoration, such as single surface occlusal amalgam on molar teeth, would show slightly better survival, since it would be presumed that a second single-surface amalgam was in a different location from the first. However, the appropriateness of using such rules is debatable, since from a patient's point of view the tooth has still received a re-intervention. In any case, Robinson's rules could not be applied directly, since it is not known whether a particular single-surface amalgam was occlusal, nor whether it was the first or a subsequent restoration of that tooth.

Assessment of the state of the restoration at the time of re-intervention is not an option when looking solely at retrospective records of treatment. Although in an ideal world such a measure (using for example the Ryge or USPHS criteria) could indicate the variability in the diagnostic prowess of GDS dentists and help to explain why a dentist has chosen to intervene, it is the timing of the decision to intervene which remains the concern of the patient.

This analysis reflects the real decisions made in high street dental surgeries, with the clinical diagnosis and treatment planning performed by practising dentists, rather than a view from an external assessor which, though calibrated and standardised, may be less realistic in its recommendations for treatment. The reasoning behind any decision to re-intervene is properly the subject of further research, but not of immediate relevance here.

The survival curves indicate that the patterns derived from the early life study (section 4.1) continue into the following ten years. Again, the more complex the cavity the shorter the expected time from restoration to re-intervention. Tooth coloured restorations generally perform less well in this respect than amalgam. This is in line with most of the existing literature (especially in section 2.6.1), and may reflect the difficulty of finding tooth coloured direct filling material to match the physical resilience of dental amalgam. It may also reflect the different sites in which different materials are used.

The ‘worst’ performing material was invariably glass ionomer. This material relies on adhesion rather than retentive cavity preparation for retention, and so involves less removal of dentine. Although re-intervention, particularly in the form of re-intervention with another glass ionomer filling, may occur frequently, it is at least possible that the life of the tooth, if not that of the restoration, may be greater for a glass ionomer restoration than for an amalgam. Although frequent replacement of restorations may be inconvenient and expensive, it may be preferable to the earlier loss of the tooth after fewer but more invasive interventions.

5.4.4 Tooth position and Patient Age

Tooth position is clearly relevant. There are effectively three groups (Figure 4.23). Third molars (tooth position 8) survive restoration best, possibly because most of the restorations of third molars are single surface occlusal amalgams. Anterior teeth have consistently the worst survival to next intervention. This is clearly confounded with the poorer survival of tooth coloured restorations – incisors and canines are generally restored with composite resin or glass ionomer. Similarly, most of the restorations on the third group – premolar teeth and the first and second molars – are made with dental amalgam, and have better survival to next intervention than anterior teeth.

Patient age is also clearly important – with restorations in younger patients surviving longer. Ages are averaged across the eleven year observation period, but only the earliest restorations are tracked for a full ten years, so the shape of the extreme right of the chart (Figure 4.25) is determined by the restorations placed at the start of the period.

A possible explanation for the age effect is that while most of the restorations in younger patients are in virgin teeth, older teeth are more likely to have existing restorations, and the re-intervention could be triggered by problems with any of these existing fillings. Existing restorations may also weaken the tooth structure, leading to a greater likelihood of fracture. The tooth structure may in any case be further compromised by deterioration of the dentine as a correlate of patient age.

5.4.5 Patient History

The treatment and attendance history of the patient provides two measures which might be regarded as proxies for state of oral health: frequency of attendance (Figure 4.39) and average cost (Figure 4.40), taken over the whole period from first to last treatment record for the patient. The strong relationship of both these indicators to survival to next intervention suggests that incorporating a calibrated oral health measure into treatment selection might improve the estimation of the prognosis for the tooth.

The two remaining aspects of patient history – change of dentist (Figure 4.41) and change of charge-paying status (Figure 4.42) – appear to have an influence on interval to re-intervention in the direction that would be expected. A new dentist may be more likely to intervene because he or she is personally unaware of what lies beneath an existing restoration. If patient charges act as any deterrent to the seeking or acceptance of dental treatment, then it might be expected that intervention and re-intervention rates would be higher when a patient subsequently changes from paying to non-paying, and vice versa.

5.4.6 Other Factors

All the other factors, at a univariate level, make relatively little difference to the survival curve. Sex of patient, sex of dentist, region, time, and even the charge-paying status of the patient, give almost indistinguishable curves, as does the level of fluoridation of the water supply.

More distinctive, but nevertheless small, differences are associated with some of the characteristics of the dentist, specifically age and experience, employment status, and country of qualification. It does appear that younger dentists, including those employed as vocational dental practitioners, achieve longer intervals from restoration to re-intervention than their older colleagues. The earliest vocational trainees may have been highly motivated since vocational training did not become mandatory until 1993. The age effect may also reflect different treatment philosophies – the older dentist may attempt to fill a tooth which a younger dentist might extract or crown. This issue is considered further in the discussion on particular subgroups (section 5.4.8).

5.4.7 Type of Re-intervention

The analyses of type of re-intervention (section 4.3.4) indicate that the first one or two years after restoration are different from the long-term pattern. For all materials, the rate of replacement with the same material grows in the first few months, suggesting that very early failure may prompt a revised treatment plan.

The overall pattern (Figure 4.43) is dominated by amalgam (Figure 4.44). The steep rise in the proportion of amalgam re-interventions in the first year reflects a reduction in the proportion of crowns and extractions, particularly the latter. In the former case this may reflect a conscious treatment plan to use an amalgam filling as a core for a crown. In the case of early extractions, it may indicate an inappropriate choice of initial treatment, resulting in the patient having to undergo both the cost and discomfort of a restoration, only to lose the tooth soon afterwards.

Resin composite restorations (Figure 4.45) show the least variation in re-intervention type and material, though for the first few months there is an increased hazard of re-intervention by crowning of the tooth.

For glass ionomer (Figure 4.46), the proportion retreated with the same material reaches a peak after about a year, then over the next ten years there is a gradual transition from glass ionomer to composite resin. The first few months are similar to those for the other materials, but there does not appear to be any obvious reason for the long-term decline in the use of glass ionomer as a replacement material.

5.4.8 Particular Subgroups and Associations

The subgroup analyses (section 4.3.5) provide a cautionary warning about the inference of cause and effect, particularly from observational studies. The year of placement has been incorporated into several of the analyses (Figure 4.47 and Figure 4.48) in an attempt to tease out whether there has been an underlying improvement in the interval between placement and re-intervention, after other factors have been taken into account. It would appear, from this analysis, that not only has there not been an improvement, but that survival has generally declined, albeit modestly, over the observation period. This might reflect a tendency to intervene more readily, or may be related to restoring teeth which might previously have been crowned or extracted. Most, but not all, of the residual difference between restorations placed in different years disappears when age is used to standardise the charts (Figure 4.50 to Figure 4.55). The fluctuation from one year of placement to the next in glass ionomer restorations on molar teeth (Figure 4.54 and Figure 4.55), may to some extent be explained by sampling error, since such class V restorations are relatively much rarer than amalgam fillings

The general improvement in oral health over time might be expected to result in improved survival, unless the improvement is confined to improvement in the number of filled rather than extracted teeth. In that case the average survival would be reduced by heavily restored teeth which have been saved from extraction.

The relationship between patient age, dentist age, and type of treatment is complex. Patient age is still closely associated with survival, but the relationship within each type of treatment is non-linear, with the reduction in survival being concentrated at different ages. This may reflect the sequence in which different teeth develop decay and fractures – starting with posterior teeth and gradually progressing to incisors and canines. This could perhaps be attributed to age-related changes in the dentine. Composite resin on incisors and canines could therefore be expected to perform near its best for longer than any restoration on molar teeth.

The difference between the patterns for glass ionomer and amalgam on molar teeth is more difficult to explain, but may be related to changes in the adhesive or other properties of teeth at different ages. For example, glass ionomer may not bond well to sclerotic dentine. For glass ionomer there is a sharp drop in survival after age 30, but then no further change with increasing patient age (Figure 4.58).

Dentist age, noted from univariate analysis as associated with poorer survival, still persists as a factor within each type of patient and age of patient (Figure 4.56 to Figure 4.58). Older dentists do indeed tend to have older patients, but the subgroup charts show that this does not fully explain why older dentists have relatively poorer survival from restoration to next intervention.

In addition to the suggestion that more experienced dentists may make bolder intervention decisions, there are several other possible explanations. We cannot discount the possibility that newly qualified dentists may have, on average, a higher technical competence than those whose training dates from several decades earlier. The current emphasis on continuing professional development may help to address this issue. There is also a physical issue, in terms of manual dexterity and acuteness of eyesight which may generally be considered to deteriorate with age.

The analyses of average annual cost and median re-attendance interval against patient age (Figures 4.52 to 4.57) demonstrate that while the two proxies for oral health clearly remain major correlates of survival, whatever the age of the patient, there remains, for most types of restoration, a strong relationship with patient age. The exception is glass ionomer on molar teeth, which seems unrelated to patient age, once the average cost or median interval has been taken into account.

It is possible to carry out many more bespoke analyses of particular subgroups of the data, but a more over-arching analysis can be achieved by using a model which incorporates all the potentially relevant variables, as discussed in section 5.5.3.

5.4.9 Replication

The opportunity to conduct a full-scale replication of such a large analysis as this is rarely available to the researcher. The replication demonstrates that, whatever the limitations of the estimates of standard errors, the main conclusions about the survival of restored teeth to next intervention are extremely robust. There is room for much debate when it comes to interpreting the findings, but at least the element of sampling error has been effectively eliminated.

5.5 Modelling

5.5.1 Inflexions at Six months

The purpose of these two simulations was to demonstrate that the shape of the survival curve, in respect of its departure from a smooth change of gradient, could be explained by the GDS pattern of regular checkups, which occur at intervals closely clustered around six months.

The values for the scale parameter were found by trial and error, but a systematic computer-intensive maximum likelihood algorithm could be devised to generate values which provided the best fit to any particular set of observed data. Similarly, the choice of exponential was made for simplicity – it commonly approximates to the distribution of waiting times for random events and there is some support for this choice from previous analyses (section 4.3.3.2). The model could be generalised to a Weibull or high order polynomial to fit the data better. Nevertheless, the second simulation (Figure 4.70) is reminiscent of observed survival curves, particularly for glass ionomer (Figure 4.1 and Figure 4.5). The attenuation over time is also apparent in the observed survival curves (Figure 4.21).

There are several reasons why a re-intervention may coincide with the timing of a routine check-up examination. In particular, the intervention may not be urgently needed from the patient's point of view. Indeed, the patient may be unaware of the need for re-intervention. The patient may defer treatment until his or her next routine appointment, if it is reasonably soon. It does not follow that lengthening the interval between routine appointments would reduce the level of interventions, nor that the intervals between interventions would be lengthened, since a patient with a problem might choose to contact his dentist sooner rather than later if there were a long interval before the next routine appointment.

Although the effect is noticeable in the first year or two, it remains the case that most early re-interventions are not clearly associated with routine examinations, so it is likely that the dentist had to provide treatment in these cases at shorter notice than usual. The attenuation of the inflexions in subsequent years is attributable to the variation, around six months, in the re-attendance interval, but there is no reason to suppose that the level of unplanned re-intervention is any lower for later re-interventions. For this reason the re-intervention level is a matter of considerable concern for practice managers, who need to allow more flexibility to cope with unplanned courses of treatment resulting from a need to re-intervene on previously restored teeth.

5.5.2 Simulation of Cross-sectional Distortion

These simulations were designed to show the dangers of using the unadjusted distribution of the age of replacement of restorations in a cross-sectional study. Section 2.5.3 details several such studies.

Nearly all of these studies assumed that restorations which received interventions other than replacements could be ignored, yet, as can be seen from the charts in section 4.3.4, a disproportionately high number of early re-interventions consist of extractions and crowns, precisely the type of re-intervention commonly ignored in cross-sectional studies. Such studies therefore tend to overestimate the time to re-intervention.

The assumptions about historical provision are equally important, and there is widely documented evidence that in general, over the last decade, the numbers of amalgam restorations have been falling, and the numbers of tooth coloured restorations rising (section 2.7.1). Consequently, cross-sectional studies are likely to have over-estimated the interval to re-intervention of the former and underestimated that of the latter. In any case, account should have been taken of the specific history of the dentists included in each research study. In practice, in the absence of comprehensive retrospective computer records such as those held by the DPB, it is not practicable to do this, and indeed some studies had to exclude a substantial number of records because the date of placement of the replaced restoration could not be retrieved. This may have compounded the distortion.

The third method (Nelson-Aalen) described in section 3.3 combines cross-sectional re-intervention and cross-sectional restorations *in situ* to avoid the need for such historical data.

5.5.3 Cox-Regression Model

The model described in section 4.4.3 is restricted to a sub-population of the overall sample, and this may have led to some distortion of the relationship between the variables. The restrictions were imposed in order to minimise the dependency on adjustment for re-attendance probability by ensuring that no case had more than two years before the natural censoring at the end of the observation period (December 31st 2002). By insisting on at least four attendances the more extreme variations in median interval between attendances and mean annual gross fees were also avoided. Tunnel restorations and root fillings without direct fillings in the same tooth were omitted because the univariate Kaplan-Meier charts suggested that they were inconsistent with a proportional hazards model. In the case of this group of root fillings, this may have been a consequence of the heterogeneity of the associated treatment (crowns, inlays, bridges, veneers).

It must also be remembered that the model, though statistically a good fit, rests on assumptions about both the proportional nature of the hazards associated with different covariates and about the linear nature of this relationship. Correlations between covariates inevitably result in ambiguity of interpretation, since the prioritising of one covariate over another can be dependent on the particular sample chosen. The appendix contains, for reference, a correlation matrix for the regression coefficients.

In summary therefore, the Cox-regression model should be seen as an attempt to gain deeper insight into the relationship between the available covariate variables and the associated distribution of times from placement to re-intervention.

Overall, there are few surprises, though the quantification is useful, and the opportunity to unpick the associations between, in particular, tooth position, type of restoration, age of patient, and other covariates is valuable.

The most dramatic associations are, as noted from the univariate analyses, those with patient age, mean annual scale fees, and median interval between attendances. In each case only the linear component has been used, and it may be that a more complex relationship could be revealed.

Tooth position and type of treatment are also closely associated with time to re-intervention. However, the pattern is not quite the same as in the univariate analyses. Once all other factors have been taken into account, we still have third molars surviving longest, but in this model first and second molars fare worst and premolars join incisors and canines in between these two extremes. On treatment type there is still a hierarchy within amalgam restorations with single surface amalgams lasting longest and MODs lasting for the shortest time from placement to re-intervention. The relationship with tooth-coloured restorations is a somewhat different, since composite resin is, in this model, comparable with single surface amalgam, while glass ionomer is comparable to MO or DO amalgams, rather than worse than MOD.

The explanation for this lies in the definition of the variables COMP and GLASSION, which are set to the value 1 for every tooth treated which has treatment by, respectively, composite resin or glass ionomer. Any tooth for which composite resin or glass ionomer as the main treatment (MAINTRT), will therefore have COMP or GLASSION set to 1. The hazard ratio (Exp(B)) for comparison with a single surface amalgam is therefore estimated as the product of Exp(B) for MAINTR(4) and that for COMP, in the case of composite resin, and correspondingly for glass ionomer, rather than just Exp(B) for COMP. From Table 4.70 it can be seen that for composite resin the ratio is 0.990 times 1.294, equal to 1.281. For glass ionomer the hazard ratio is similarly 1.147 times 1.219, equal to 1.398. These hazard ratios restore composite resin and glass ionomer to their observed univariate relative survival curve positions.

One of the ‘associated’ indicators, AEXAM, appears early in the model (Table 4.69). This indicates that a filling provided within a course with an examination has a much better prognosis than one provided in a course without examination, for example under emergency conditions. Possible explanations could include an intrinsic additional hazard in a tooth presenting at such a late stage that the patient is conscious of the need for restoration – advanced caries or material fracture for example – or perhaps a restoration provided with less than ideal timing, by a dentist having to squeeze an additional appointment into an already crowded day. Against this it should be noted that ARECALL was not significant – there is no indication that restorations placed when a dentist has claimed a recalled attendance to open his surgery in an emergency have any worse life expectancy than others.

The significant ‘associated’ covariates fall into two groups, those associated with higher hazard – glass ionomer fillings, extractions and dentures – and those associated with lower hazard. In addition to examinations, this latter group includes radiographs, periodontal treatment, other amalgam fillings, veneers, inlays, crowns and bridges. Extractions and dentures suggest an oral state which is in terminal decline through loss of teeth, while most of the ‘lower hazard’ treatments suggest active conservative dentistry, which may in turn be associated with better oral hygiene.

The remainder of the 32 covariates agree closely with the univariate findings, and are all intuitively plausible in their estimated effects. Modifiers of the treatment on the tooth, such as additional treatments including restoration of incisal edges or angles, pin or screw retention, and root fillings, all introduce additional hazard. Charge-paying status and change of dentist also have the association which would be expected. The univariate observation about the ages and countries of qualification of dentists also persist in this model.

Year of placement may be compromised by the subselection criteria for this model, so this aspect of the model should be treated with particular caution. Patient sex does appear still to be significant, though it is not yet clear whether this is dominated by the data for intervention in the first year or whether confounding with other variables has hidden the relationship over longer time periods from the univariate charts.

Finally, it is worth noting those variables which do not appear to be associated with variation in expected time from restoration to intervention. Fluoride in particular continues to be unassociated. The others, in addition to AMALGAM which is linearly dependent (section 4.4.3) and ARECALL, discussed above, are inlays on the same tooth (very rare), and four other associated treatments: composite resin, root fillings, sedations, and domiciliary visits. Sedations and domiciliary visits are rare in association with fillings, while it is possible that composite resin and root fillings may already be represented by some other correlated indicator covariate such as radiographs.

The Cox-regression model is a valuable characterisation of the empirical evidence on the distribution of intervals between restoration placement and next intervention. The method is however only semi-parametric, so that the shape of the curve remains a matter of empirical discovery. The curve-fitting exercise was undertaken in order to explore whether a reasonably simple parametric function could adequately describe this empirical curve (Figure 4.73).

The simplest curve, the exponential based on a constant hazard (yellow in Figure 4.74) underestimates the hazard in the early years and is over-pessimistic about longer-term survival. However, it is almost coincident with the base survival curve at the median, and might provide an adequate basis for a crude characterisation of the survival curve.

The Weibull model (magenta in Figure 4.74) is a close approximation to the base hazard, though it errs on the side of pessimism in the first couple of years. The Weibull has the useful mathematical property that when hazards are proportional and the base survival function is a Weibull then the survival functions for subgroups are also Weibull with the same shape parameter. Over the range of times considered in this research there is no indication of increasing hazard with age, but one of the limitations of the Weibull distribution is that the hazard function is monotonic.

A cubic survival function, because it has an underlying quadratic hazard function, allows this ultimate increase in hazard, which is intuitively plausible (an extremely old tooth might be expected to be more fragile than a younger one). It should be remembered though that the time interval estimated is conditional on the patient remaining ‘at risk’. If a patient dies then the method of estimation used ensures that any restorations are censored at not more than one year after the last attendance. The fitted cubic (green in Figure 4.74) follows the baseline survival curve very closely, and it is only at the end of the eleven years that it suggests lower cumulative survival than the empirical estimates.

In principle therefore, the results obtained so far enable an algorithm to be set up which can calculate, for any patient who has recently received a directly placed restoration, the likely cumulative survival curve for that restoration, given up to 32 different risk factor measurements, concerning the patient, the dentist, and the characteristics of the tooth, the cavity and restoration material. Where on clinical, economic or other grounds a dentist has a balanced choice between different types of direct restoration, these findings may help to inform that decision.

However, these findings do not ‘prove’ that one type of restoration is ‘better’ than another. Only a randomised clinical trial can test whether, *in the same circumstances*, treatment A is better than treatment B. Nevertheless, what this work does show is how long restorations last, as currently provided in the General Dental Services.

5.6 Clinical Significance

The distribution of survival time to re-intervention in the General Dental Services may arguably be regarded as the norm rather than the exception, both within the UK and perhaps in other industrialised countries. Most dentists in the UK carry out most of their treatment in the GDS, and most patients receive most of their dental treatment from GDS dentists (Buck and Newton, 2001). Indeed, virtually all UK-trained dentists start their careers working in the GDS, currently entering as vocational dental practitioners.

While the method of remuneration in the GDS may encourage more frequent examinations than, for example, one based on salary or capitation, there is little difference between the re-intervention intervals for vocational dental practitioners or salaried assistants and those of their item-of-service based principal colleagues (Figure 4.32). Certainly, the differences are much smaller than, for example, those between patients of different ages (Figure 4.25).

As for international comparisons, the existing literature on the proportion of replacement restorations (section 2.3.1) places the UK close to the USA and Scandinavia, though the variation between different estimates, even in the same country, is huge. The balance of treatment philosophy between different countries may vary, but the indications for direct restoration are common across international frontiers, and the UK regularly receives an influx of dentists trained in other parts of the world. It is implausible to suppose that these incoming dentists immediately change their techniques of diagnosis and restoration placement when they start practising in another country. The evidence of this study (Figure 4.33) is that, certainly in Europe, there is no distinction to be drawn between different countries of training.

It is therefore reasonable to conclude that the lessons from this work, particularly the relative risks associated with different characteristics of dentists, patients, tooth position and type of restoration, are likely to translate into useful insights for dental research throughout the world.

These research findings provide a reliable empirical benchmark against which individual dentists can monitor their own outcomes, and by means of which local health authorities can review the achievements of primary dental services in their areas.

The methodology developed within this work may enable clinicians to measure their own distributions of re-intervention intervals. Additionally, the Dental Practice Board could employ these methods to provide the framework for individual practitioners to perform clinical governance in respect of the performance of their treatments.

The findings also furnish the Department of Health and the dental profession with robust quantification of the current state of re-intervention activity within primary dental care, as a basis for developing future policies for resources and training.

6 CONCLUSIONS

6.1 Conclusions from the Literature Review

5. **The empirical estimates of median survival of directly placed restorations in the literature are generally around ten years, varying up or down according to the materials and population. Factors thought to affect survival include materials, size of cavity, and patient and operator characteristics, but few studies have been sufficiently large to detect significant differences.**

6.2 Key Empirical Conclusions

6. **Overall, median survival for directly placed restorations in the GDS was slightly more than eight years from restoration to next intervention on the same tooth. After ten years, the percentage of directly restored teeth surviving without further intervention was 46%.**
7. **Restoration material, type of cavity, tooth position, patient age, patient treatment history and patient attendance history are all important risk factors. Ten year survival rates ranged from 37% for glass ionomer fillings to 57% for single surface amalgam fillings; and from 28% for patients with high average annual treatment cost to 65% for patients whose average annual treatment cost was low.**
8. **Other less important, but still statistically significant risk factors include age and experience of dentist, which are both negatively correlated with survival rates, and the year of placement of the restoration, which is also negatively correlated with the survival rate.**
9. **The relative survival of different groups of restorations in the first year continues over a longer period. However, the survival curve for the first year contains an inflexion at around six months, which may be associated with a six-monthly check-up inspection cycle.**
10. **Overall, one-year re-intervention rates were around ten per cent for patients aged 35, with single surface amalgam restorations having a 5% re-intervention rate, compared with nearly 13% for glass ionomer fillings.**
11. **A comparison with the interval to next intervention for teeth not restored at the same time, but in the same position in the same mouth, showed that directly placed restorations do not restore a tooth to as durable a condition as other teeth.**
12. **Most re-intervention treatments were of the same type as those used for the original restoration, but there was a greater**

proportion of crowns and extractions for those re-interventions occurring within the first year after placement of the original restoration.

13. **Various subgroups of restorations have been analysed graphically, in particular to explore the association between patient age and other characteristics of the restored tooth.**

6.3 Methodology

14. **The DPB has a comprehensive statistical archive which has provided definitive observational evidence on the intervals between restoration and re-intervention within an NHS high street dental surgery setting. This research has demonstrated the practicability of using data from this archive to quantify the survival of dental restorations.**
15. **New statistical methods have been developed to enable administrative data covering an eleven year observation period to be used successfully to estimate longer-term survival of restored teeth from restoration to re-intervention.**
16. **Statistical methods not previously used in dentistry have been used on cross-sectional data to estimate survival curves for the time from restoration to next intervention.**
17. **These methods have been shown to be effective in reproducing survival curves based on Kaplan-Meier analysis over longer periods of observation.**

6.4 Statistical Conclusions

18. **A Cox-regression proportional hazards model has been constructed to fit the observed DPB data, providing quantification of the relative hazards associated with different characteristics of the restored tooth, the dentist, the surgery, the patient, and the treatment.**
19. **A total of thirty-two different variables were identified in the model as contributing to the hazard of re-intervention. All those variables identified graphically were also major covariates in the model.**
20. **The underlying baseline survival curve can be closely modelled by either a Weibull or a cubic function.**
21. **The robustness of the findings has been demonstrated by replication of the whole eleven year analysis on a completely separate sample covering the same period of time, with very similar results.**

7 SUGGESTIONS FOR FURTHER WORK

The research documented in this thesis has made substantial progress in several areas of both dental empirical evidence and statistical methodology. It has also opened several fields for further research. These are briefly described in the following sections.

7.1 Continuing Work on DPB data on Fillings

Further years of data have now been accumulated, so there is the opportunity to extend the analyses towards the complete life history of directly placed restorations. There is also more extensive complete data for recent years, so that the performance of rarer types of restoration, such as tunnel amalgams, can be explored on large samples.

The work on the early life of restorations can also be extended to consider other covariates, again using an even larger dataset. In particular this will enable personalised survival profiles to be prepared for individual dental practitioners, as an independent measure for use in clinical audit and peer review, and also as a probity assurance measure for detecting dentists who have persistently short average intervals between interventions on the same tooth.

7.2 Other Types of Intervention

The techniques developed on directly placed restorations are readily transferable to other interventions carried out in the GDS. These interventions include crowns, inlays, veneers, bridges and dentures. In particular, the presence of root fillings can be tested as a risk factor for the survival to next intervention for these other interventions.

When a comprehensive analysis of observed survival behaviour of all restorations has been completed, then it will be possible to measure the effectiveness of the full range of alternative dental treatments in terms of expected years of service.

7.3 Statistical Methodology

The methods used for adjusting for censoring developed in the present study can be further refined to allow systematically for a wider range of factors associated with different propensities of patients to re-appear for treatment. This could involve the use of multiple linear, logistic or log-linear regression.

Instead of modifying the Kaplan-Meier modules of existing statistical packages a new set of algorithms can be developed to estimate the survival function directly.

There is also scope for developing the statistical methodology to allow for the clustering of the eleven year sample resulting in over-optimistic standard errors, by using either frailty analysis or multi-level modelling.

Finally, there is great scope for developing and refining the statistical models which have been created. Methods can be developed to optimise the parameters for the six-month inflexion model, using an iterative maximum likelihood methodology. There is much further testing and extension work to be carried out on the Cox-regression model, facilitated by the rapid fall in the costs of computer processing.

7.4 Further Gathering of Direct Evidence

All the evidence produced in this thesis may be regarded as indirect, since it is based on payment claim records rather than direct clinical observation. There are two major areas of direct evidence which may be explored as complementary work to validate and extend the conclusions drawn from this indirect research.

The first concerns the cross-sectional analysis methodology. The practicability of using the methodology developed in section 3.3 can be tested with volunteer GDPs, and the results validated against DPB data. Furthermore, the direct observations by these dentists should give insight into the proportion of interventions which can be directly associated with the previous restoration of the tooth.

Secondly, the eleven-year analysis has suggested a variety of causal links. These can be tested only by means of appropriate randomised controlled clinical trials.

7.5 Pilot Study on the Use of DPB Data for Individual Dentists

The data held by the DPB can be used to provide individual dentists with personalised analyses of the survival of their restorations to next intervention. There is scope for working with a group of volunteer dental practices to explore the use which could be made of such information to modify individual prescribing philosophy and the resulting clinical outcomes.

7.6 Wider Implications For Dentistry

Particularly as the number of years of available data grows, it becomes possible to take an overview of the life of individual teeth across a whole series of interventions. In particular, it is possible to chart the sequence from virgin tooth through various interventions, noting the intervals between them, and the time to various landmark events, such as the initial restoration, the first root filling, the first crown, the eventual extraction, and the provision of bridges and dentures. This could include a backward look at the precursors to such events.

This more holistic view of the total life of the tooth may help to resolve some of the existing debates as to whether frequent glass ionomer restoration is preferable to less frequent amalgams. Ultimately, it is the survival of the teeth themselves, rather than that of individual restorations, which is of greatest importance.

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9 GLOSSARY

aggregation	In a statistical context, aggregation is the creation of a set of summary statistics for groups of records, such as sums or averages.
anterior	Anterior teeth are those at the front of the mouth, comprising incisors and canines.
approximal	Approximal surfaces are those which are actually or nearly in contact with each other.
arch	The mouth has two dental arches, upper and lower, each normally containing a set of up to sixteen teeth.
asymptomatic	A condition is asymptomatic if the patient can feel no pain or other abnormal sensation and the dentist can see no conclusive clinical indications of the condition.
buccal	The buccal surface of a tooth is on the outside, nearest to the mouth. It is also referred to as the labial surface.
canines	The four canine teeth are the pointed teeth between the second incisors and the first premolars. Their tooth notation is 3. They are also referred to as cuspids or eye teeth.
capitation	A capitation payment system is based on payment according to the number of patients registered with the dentist, irrespective of what treatment the dentist provides to those patients.
caries	Dental caries is a disease which causes decay to the substance of the tooth.
censoring	Censoring is said to be present when the time of the start or end of a life is not known exactly.
composite resin	Composite resin consists of a class of non-metallic plastic restoration materials used to provide tooth-coloured fillings.

Company Dentists	Company Dentists are employed by companies to provide dental services, generally to other employees of the company.
Community Dental Service	The Community Dental Service (CDS) consists of salaried dentists employed by the local Health Authority to provide primary dental care to particular subgroups in the local population, such as children and the disabled. The CDS also provides non-treatment services such as oral health promotion and surveillance programmes.
Corporate Bodies	Corporate bodies are companies which are authorised to carry on the business of providing dentistry. They are strictly limited in number, and they may employ dentists to carry out work within the General Dental Services, or privately.
course of treatment	In the GDS, a course of treatment consists of all the treatment which is required to maintain oral health for the time being, with the added proviso that it is also restricted to the amount which the patient is prepared to undergo. It excludes any treatment provided privately.
dental amalgam	Dental amalgam consists of a mercury-based mixture of substances used to restore teeth. Amalgam fillings have a grey or silvery appearance.
dental contract	When a dentist wishes to work within the GDS he or she must register the location of the surgery and details of assistants and associates with the local health authority. The DPB checks these details and issues a ‘dental contract number’, which must be quoted on every payment claim made by the dentist.
distal	The distal surface of a tooth is the surface furthest from the centre of the dental arch of which the tooth forms part. The opposite side of the tooth is known as the mesial surface.
edentulousness	An edentulous patient is one who has no standing teeth.

empirical	An empirical statement is one based on observation alone, without the support of theoretical deductions.
gamble questionnaire	A technique for encouraging participants to provide researchers with estimates of probability by trading possible outcomes against the expenditure of money or other resources.
General Dental Services	The General Dental Services (GDS) are the main providers of primary dental care in England and Wales. They are staffed mainly by dentists who have the status of independent contractors, who receive payments from the National Health Service and from patients according to a fixed price list for item of service provided.
gingival	Concerned with or close to gums. The gingival third of a tooth surface is the one third part closest to the gum.
glass ionomer	A synthetic material used for filling and sealing teeth. An alternative to composite resin.
Hospital Dental Service (HDS)	The Hospital Dental Service provides both secondary and primary dental care, the latter in its role as a provider of teaching services for dental students through University Dental Schools.
hazard function	The hazard function of a survival process is defined as the short-term death rate.
iatrogenic	Iatrogenic means caused by the medical, or in this case dental, practitioner.
implant	A dental implant consists of an artificial tooth secured to a post which is imbedded directly in the bone of a patient’s jaw.
incisal angle	The incisal angle of a tooth, usually of an incisor, is the cutting edge.
incisors	The incisors are the eight teeth at the front of the mouth, in tooth positions 1 and 2.

item of service	In the context of payment systems, item of service consists of a specified action (usually a treatment or combination of treatments), for which a prescribed fee is payable to the dentist.
labial	The labial surface of a tooth is that closest to the patient's lips.
lingual	The lingual surface of a tooth is that closest to the patient's tongue.
longitudinal	A longitudinal dataset consists of measurements at different times on the same experimental subjects. In the dental context, this takes the form of a sequence of records for the same group of patients, where the records consist of information about the patient's dental history at different times, generally covering several years.
mesial	The mesial surface of a tooth consists of the surface nearest the centre of the dental arch, where the two central incisors (tooth position 1) meet, mesial to mesial.
molars	Molar teeth consist of the twelve adult back teeth, tooth positions 5, 6 and 7.
National Health Service (NHS)	This is the government service which manages and provides all state-subsidised health-related services in the United Kingdom.
New Contract	The New Contract, introduced into the GDS in October 1990, involved a major change in the system for paying GDS dentist. In particular, it introduced capitation payments in addition to item of service.
occlusal	The occlusal surface of a tooth is the surface which meets the teeth on the opposite dental arch – it is the biting surface.

parametric	A parametric statistical model assumes an underlying structure to the observed data, characterised by mathematical relationships between a set of unknown constants referred to as parameters. Parameters have values, which can be estimated from the observed data.
payment schedule	Payments to GDS dentists are gathered together in a monthly payment schedule, which lists all the components, including the treatments provided to patients, which account for that month's gross fees.
Personal Dental Services	Personal Dental Services (PDS) consist of a series of innovative pilot schemes for the organisation and funding of primary dental care, as an alternative to the GDS and CDS. The first PDS schemes started in October 1998.
postcode	All addresses in England and Wales have been issued with an alphanumeric code which identifies, to within a group of up to about 150 neighbouring addresses, the location of the address. Look-up tables are available which can associate postcode with various other geographical data, such as grid reference.
posterior	Posterior teeth are those at the back of the mouth – the molars and pre-molars.
postgraduate training	GDS dentists are entitled, and in some cases required, to undertake post-graduate training. This may take various forms, ranging from the year spent as a vocational dental practitioner after graduation to specialist courses in, for example, orthodontics or endodontics.
pre-molars	Pre-molar teeth consist of those in positions 4 and 5, between the canines and the molars. Pre-molar teeth are sometimes referred to as bicuspids.

prior approval	For certain items, and for courses of treatment where the expected total fees will exceed a prescribed threshold, GDS dentists are required to seek and receive prior approval from the DPB before they may start treatment.
Primary Dental Care	Primary dental care is the first point of contact between patients and the dental profession. In England and Wales the services provided in primary dental care range from oral hygiene instruction through a range of conservation and prosthetic procedures, including complex oral surgery, crowns and bridges, and orthodontics.
Private Dentistry	All dentists registered with the General Dental Council (GDC) are permitted to treat patients privately, at fees mutually agreed between dentist and patient. This treatment may be provided instead of, or in addition to, treatment provided under the auspices of the NHS.
pseudo-random	A pseudo-random method of selection uses digital computer programs to generate numbers which are distributed in a way which appears to be random.
quadrant	Each dental arch is divided into two quadrants: right and left, from the viewpoint of the patient.
remineralisation	Remineralisation consists of a process of natural recovery of a tooth, involving the reversal of tooth decay following a caries attack.
SAS	The name of a statistical software package, and of the company which supplies it.
Secondary Dental Care	Secondary dental care is generally provided in a hospital setting, on referral from primary dental services. The main services provided in secondary dental care are within the Maxillo-facial, Oral Surgery and Orthodontic specialties, as well as most treatment carried out under general anaesthetic (indeed, all such treatment after January 2002).

sign test	A statistical test in which a statistical measure is calculated for each experimental subject and the observed pattern of positive and negative values is compared with what would be expected from a random variable with a zero expected value
stratifying	Stratifying is a statistical technique used to increase the extent to which a sample contains members typical of the diverse subgroups which make up the population from which the sample is selected. It consists of dividing the population into a set of groups, known as strata, and then drawing a subsample from every stratum. The resultant stratified sample consists of the combined members of all the subsamples.
survival curve	A survival curve charts the survivor function, defined as the proportion of a population which is expected to survive for longer than any particular period of time. At time zero the survivor function has the value 1. It then declines towards zero, when all a population subject to the survival process are expected to have died.
trauma	Trauma consists of injury resulting from an external mechanical cause, such as (in the dental case) a blow to the jaw.
Vocational Dental Practitioners	Since 1993 all newly qualified dentists in the GDS have been required to undertake a year's vocational training under the supervision of an approved GDS principal. Until this vocational training has been completed, GDS dentists are not allowed to practise as principal dentists.

10 APPENDIX

The appendix consists of a set of HTML documents arranged within sub-folders within the accompanying CD-ROM. These documents have been produced as output from custom-written programs using the statistical analysis package SPSS. The disk also contains the complete text of this thesis, in the form of a Microsoft Word master document with sub-documents.