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Evaluation of the cost-effectiveness of root canal treatment using conventional approaches versus replacement with an implant

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Abstract

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Aim To evaluate the cost-effectiveness of root canal treatment for a maxillary incisor tooth with a pulp infection, in comparison with extraction and replacement with a bridge, denture or implant supported restoration.

Methodology A Markov model was built to simulate the lifetime path of restorations placed on the maxillary incisor following the initial treatment decision. It was assumed that the goal of treatment was the preservation of a fixed platform support for a crown without involving the adjacent teeth. Consequently, the model estimates the lifetime costs and the total longevity of tooth *and* implant supported crowns at the maxillary incisor site. The model considers the initial treatment decisions, and the various subsequent treatment decisions that might be taken if initial restorations fail.

Results Root canal treatment extended the life of the tooth at an additional cost of £5–8 per year of tooth life. Provision of orthograde re-treatment, if the root canal treatment fails returns further extension of the expected life of the tooth at a cost of £12–15 per year. Surgical re-treatment is not cost-effective; it is cheaper, per year, to extend the life of the crown by replacement with a single implant restoration if orthograde endodontic treatment fails.

Conclusion Modelling the available clinical and cost data indicates that, root canal treatment is highly cost-effective as a first line intervention. Orthograde re-treatment is also cost-effective, if a root treatment subsequently fails, but surgical re-treatment is not. Implants may have a role as a third line intervention if re-treatment fails.

Keywords: cost-effectiveness, decision analysis, implant, Markov, root canal treatment.

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Introduction

Clinical decisions could be consistent and straightforward, if they were informed by unequivocal evidence, supported by clear and accepted guidelines, and if the recommended actions were universally acceptable to patients and care providers. But few areas of practice are so clear-cut. Patients are not always equipped with the information they need to make rational decisions on their short and long-term care, and healthcare agencies might equally be ill-equipped to advise on best actions for the short and long term. As a consequence, patients may submit to the paternalistic decision-making of a healthcare professional (Kaba & Sooriakumaran 2007) whose priorities may be expected to be objective, consistent and based on the same values as their own. But observations from medicine and dentistry suggest that the decisions of healthcare

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professionals themselves may be highly variable, even in the case of relatively simple interventions (Doméjean-Orliaguet *et al.* 2004, Lanning *et al.* 2005, van der Sanden *et al.* 2005, Calnan *et al.* 2007, Tickle *et al.* 2007), and influenced by a number of personal, educational and economic considerations (McColl *et al.* 1999, Brennan & Spencer 2006).

The picture is complicated further in the case of complex interventions, and interventions that may not be the final solution within the lifetime of the patient. Here, the decision-making process may be limited to a consideration of the 'next step', and informed by short-term 'success rates', assessment of immediate costs, or of the willingness of the patient to pay for that individual step. Rarely is the decision-making process informed by a detailed understanding of the relative lifespan of alternative interventions or the ongoing costs, both financial and otherwise (White *et al.* 2006, Balevi 2008), which may flow from a particular treatment decision. Restorative dental treatments are an example of such an intervention, and if patients faced with treatment decisions, or healthcare providers stewarding finite resources are to make properly informed decisions, they must be presented with information on cost and outcome which they understand and which accounts for the long-term.

The uncertainties inherent in modelling the costs of combinations of interventions over a lifetime require a fundamentally different approach to the use of evidence to that, with which most clinicians are comfortable. Decision analytic modelling provides a rational framework for decision making based on expected costs and outcomes (Raiffa 1968). Many decision analytic models are based on Markov modelling, a mathematical means of investigating stochastic or random events over time (Sonnenberg & Beck 1993). Such modelling lends itself well to the study of long-term medical conditions, defining a clear starting point or condition, and identifying a number of states into which the individual may or may not move at defined points in the future. The probability of remaining in the starting condition or moving to an alternative state is informed by best outcome and survival data, and the costs of initial and future interventions estimated from professional sources.

Markov models are increasingly used in evaluating the long-term cost effectiveness of clinical interventions from the chemoprevention of prostatic cancer to the management of heart failure (Chan *et al.* 2008, Svatek *et al.* 2008, Takao *et al.* 2008).

By contrast, the economic models applied to dentistry have generally been quite simple decision trees (Mileman & van den Hout 2003) or Markov models (Edwards *et al.* 1999) extrapolating over a fixed number of years or the assumed lifetime of a specified intervention (for example, a dental restoration), rather than over the lifetime of the patient.

Whilst previous publications have investigated the costs of dental treatments over a fixed time span (Brägger *et al.* 2005), as far as the authors are aware, this report represents the first attempt to provide a definitive examination of the cost effectiveness of common dental interventions and look at all realistic options that flow from this over the lifetime of a patient. The starting point of the Markov model is a common clinical scenario; a damaged and irreversibly pulpitic maxillary central incisor tooth, where initial treatment options include root canal treatment and restoration, or extraction and prosthetic replacement. The model explores the long-term consequences and cost effectiveness of initial and subsequent decisions for individuals at different ages. The question at the heart of this investigation is whether root canal treatment and restoration of a damaged maxillary central incisor is a legitimate and cost-effective intervention over the lifetime of an adult patient, and in comparison with the alternatives of extraction followed by either a conventional or an implant-supported restoration.

Methods

Building the model

For this study, a Markov model was built with TreeAge decision analysis software (TreeAge Software Inc., Williamstown, MA, USA, http://www.treeage.com/index.htm).

The starting point was a damaged, irreversibly pulpitic maxillary central incisor in an otherwise healthy adult male of varying age. The loss of coronal tooth tissue was defined as sufficient to require restoration with a post-retained crown. Assuming that the patient requests some treatment to fill the space, and from this starting position, the patient could occupy any of the six health states listed below at any given point in time, until the end of their life:

- Tooth extracted with resin bonded bridge (RBB) *in situ*
- Tooth extracted with a conventional bridge (fixed dental prosthesis, FDP) *in situ*

- Tooth extracted with removable partial denture (RPD) *in situ*
- Tooth root canal treated (RoCT) with a post-retained crown *in situ* (there may be repair or replacement of any of the parts of the restoration or root filling within this state)
- Tooth extracted with an implant-supported single crown (ISC) *in situ* (again this could be a first, second or subsequent restoration)
- An implant *in situ* prior to abutment connection (the transitional state during osseointegration assuming there is no immediate loading)
- Death of the patient.

The model calculated the probability of the incidence of all significant mechanical and biological complications that might arise in each of these states, over each 6 month period of the patients life, based on existing evidence (see 'Outcome data' later). A repair event or no event occurring meant that the simulated patient remained in the same restoration state, whereas complete failure resulted in transition to a different state (e.g. the event of root fracture would require extraction and replacement of the tooth with a prosthesis of some description).

The analysis was simplified by modelling the selection of a bridge or denture prosthesis as a random parameter based on likely distributions in the UK population rather than a treatment choice. The simulation terminated when the patient reached 100 years of age or died (using age-related mortality probabilities– govt. actuaries dept., life tables 2002–2004, http://www.gad.gov.uk/). The number of possible pathways through these various states in a lifetime is clearly massive. The initial treatment decision and then the potential subsequent treatments necessitated by failure of a restoration are captured in the ten major strategies outlined in Fig. 1. Whilst these cannot capture every single possibility, they were considered the most likely 10 pathways by consensus of two senior clinical academics in Restorative Dentistry (JGS and JMW).

Strategy 1 illustrates a decision to extract the irreversibly pulpitic tooth and to replace it with a conventional removable or fixed prosthesis, not an implant. The remaining nine strategies involved either retaining the tooth by root canal treatment, removing it and placing an implant or a combination of these.

In comparing each of the 10 major strategies, the costs and expected outcomes of both the initial treatment strategy (first intervention) and supplementary interventions (second to fourth intervention) are predicted. Estimations of cost and treatment longevity are central to the model. To examine fully the cost-effectiveness of three initial options (bridge/denture, implant, orthograde endodontics) the costs which might follow them are required. Clearly a RoCT is less expensive than an implant at the point of delivery but will the implant save money in the long term? To do this, it was necessary to model at least the second and third interventions and their costs and outcomes. It is not known what the patient might or should choose when the restoration fails, so all of the reasonable subsequent choices if that happened were considered and evaluated as different strategies. The strategy of placing an implant initially was also evaluated. One of these will be the most cost-effective. It was necessary to look at all of the likely second and third interventions if implants were to be given a fair comparison against RoCT.

Strategy	1st Intervention	2nd Intervention	3rd Intervention	4th Intervention
1 Extraction	Bridge/denture →			
2 One RoCT	Orthograde RoCT	Bridge/denture →		
3 RoCT then re-treatment	Orthograde RoCT	Orthograde RoCT	Bridge/denture →	
4 RoCT then surgery	Orthograde RoCT	Surgical RoCT	Bridge/denture →	
5 RoCT then Implant	Orthograde RoCT	First implant	Bridge/denture →	
6 RoCT/Implant/2nd Implant	Orthograde RoCT	First implant	2nd implant	Bridge/denture
7 RoCT/re-treatment/Implant	Orthograde RoCT	Orthograde RoCT	First implant	Bridge/denture
8 RoCT/Surgery/Implant	Orthograde RoCT	Surgical RoCT	First implant	Bridge/denture
9 Implant	First implant	Bridge/denture →		
10 Implant then 2nd implant	First implant	Second implant	Bridge/denture →	

Figure 1 Sequence of interventions in the ten treatment strategies.

Cost-effectiveness analysis: data sources

Outcome data

In order to function, the model was parameterized with information on expected treatment longevity/failure rates, and likely maintenance needs of different treatment options. Extensive Searching of MEDLINE, EMBASE, DARE and Cochrane Library databases (from inception to June 2006) was undertaken for all papers with terms including failure, fracture, success, treatment, re-treatment, replacement, complications, survival, (meta)analysis and terms describing the tooth state such as root canal, endodont#, #apical. This was supplemented by systematically checking the references of all papers retrieved for further relevant studies. Meta-analyses were utilized, where available, otherwise parameters were chosen based on the size, quality, age and selection criteria of the study. In the very rare instances where no appropriate data were available, the expert opinions of two senior clinical academics in Restorative Dentistry (JGS and JMW) were sought to define the likely limits of parameters.

Three meta-analyses were retreived on the survival of ISCs. The meta-analysis of Branemark implants (Lindh *et al.* 1998) was selected to parameterize implant survival as it differentiates between implant loss after loading and failure to osseo-integrate. A meta-analysis of prospective studies (Berglundh *et al.* 2002) provided data to parameterize complications in the implant states. However, the exclusion criteria limited the paper to a small number of studies. Hence, the analysis was judged less satisfactory than those reported by Lindh *et al.* (1998). The FDP state was parameterized using the most recent and largest meta-analysis (Tan *et al.* 2004). There are fewer reports on the survival and complication rates for RBBs and no meta-analyses were retrieved. The available data on RPDs is minimal. These states were parameterized from published individual trial or longitudinal studies where available. The heterogeneity of success criteria in reports on RoCT has defied meta-analysis to date (Creugers *et al.* 1993). Creugers analysis selected only three papers of which one (Mentink *et al.* 1993) was by far the largest, hence this report was prioritized when parameterizing the post-supported crown states. Rates of failure of root canal after *re-treatment* were taken from a 10-year Swedish study (Sjögren *et al.* 1990) whilst rates of treatment failure following surgical endodontics were based on an evaluation of apical surgery (Buhler 1988).

Costs

For the purposes of this model, typical staff time and resource use for each procedure was estimated based on a UK National Health Service (NHS) secondary care setting. Staff costs were taken from published reference costs (Curtis 2006), and costs are in UK 2006 pounds. The base case analysis for this study assumes that all implant procedures were carried out by a senior specialist (consultant) dentist. All of the conventional dental procedures were costed at more junior specialist staff (Specialist Registrar or Senior House Officer) rates reflecting the more routine nature of such interventions. Staff costs were based on mid-band salaries and included overheads, training costs and administrative support. Costs and outcomes are discounted at 3.5% according to NICE guidelines for economic analyses. Mortality is parameterized using data for UK males (2002–2004 Government actuaries department). It is important to note that the costs used are based on standard data and represent the costs to the NHS, not the price that may be paid, for example in private practice where there are a range of additional considerations, such as profit margins and variations in overhead costs.

Cost-effectiveness analysis: assumptions

In order to develop an economic model such as this, a number of assumptions need to be made. Where possible these are supported by published evidence. The following assumptions were made for this model:

- That the patient retains most of the dentition over his/her lifetime (Kelly *et al.* 2000)
- That the longevity of the restoration is proportional to the lifetime benefit of the restoration to the patient
- ISCs and crowned and root treated teeth provide the same Oral Health Quality of Life (OHQoL)
- Apical surgery is undertaken alongside orthograde re-treatment to enhance success rates, and not as a response to a distinct clinical indication such as a cyst
- RBBs, RPDs and conventional FDPs provide the same OHQoL, inferior to that of the ISC or crowned tooth. This assumption infers that the retention of a tooth unit in the maxillary anterior region in the form of the original tooth or an implant is preferable to loss of a fixed platform (natural or artificial) for restoration. Whilst it is acknowledged that this is not universally the case, this was considered a reasonable working rule, which was necessary to allow the model to compare endodontic strategies with implant strategies

- A constant hazard rate is assumed for mechanical and biological complications following an intervention
- The same hazard rate applies to an event, such as tooth fracture, in the post-supported crown states regardless of whether a surgical or nonsurgical endodontic re-treatment had occurred. The exception to this was the rate of root canal treatment failure for which there was available data (see above)
- Probability of implant loss and peri-implantitis are independent. These were modelled independently on the basis of data reported in the literature (Berglundh *et al.* 2002)
- Results are presented for UK males only on the assumption that dental costs and benefits are independent of gender. As life expectancy rather than gender dictates costs, results for females would be similar to those for a slightly younger cohort of males with the same life expectancy

The literature consists predominantly of follow-up of patients treated in dental hospitals, or in specialist clinics in the case of implants. This may not accurately reflect outcomes achieved in primary-care settings, but robust data in these environments are generally lacking. However, sensitivity analysis allowed the cost variables related to hospital staff costs to be varied (see below).

Cost effectiveness: ratio calculation

The outcome measure used in the cost-effectiveness analysis is the total longevity of a fixed platform supported crown, both root canal treated and post-crowned natural tooth, and implant supported crowns. After reviewing the costs and longevity for all ten strategies and ranking them by cost, strategies that were clearly less cost effective (those that were 'dominated' or 'extendedly dominated', see results) were removed and the rest retained for the calculation of an incremental cost-effectiveness ratio (ICER). This widely used index of cost-effectiveness (Drummond *et al.* 2005) is the additional financial cost divided by the additional effectiveness (in this case the prolonged longevity of the crown) of that strategy over the next cheapest alternative.

Cost-effectiveness analysis: sensitivity analysis

The key parameters (such as costs and survival) are all estimates and, by definition, likely to be imprecise. To allow for this, plausible ranges for key parameters (such as survival of restorations) were estimated by the academic dental authors, allowing one-way sensitivity analysis of the model to be undertaken for each of these parameters. This re-running of the model with different starting parameters illustrates the impact that the inevitable inaccuracies might have on the overall model.

The overall costs of each strategy are clearly a product of the estimated dental procedure costs. Dental costs are considerably lower in eastern European countries but average wages and hence patient budgets are also likely to be lower. However, varying the costs of dental wages or implant components will influence the *relative* cost-effectiveness of each treatment strategy. The relative effect of decreasing component costs or increasing dental salaries is likely to be similar – implant costs will fall relative to alternative restorative procedures and implant strategies will be more cost-effective. We simulated three different potential cost environments to illustrate the impact of higher and lower wage costs and the impact of lower implant component costs.

Results

Table 1 shows both the expected total lifetime costs and the expected longevity of the root canal treated tooth and/or implant supported crowns for a male aged 35, 55 and 75 years, without inflation. The values have been 'discounted' to take account for change in perceived value with time, using standard measures recommended by NICE (http://www.nice.org.uk/media/F13/6E/ITEM3FINALTAMethodsGuidePostConsultationForBoardCover.pdf) and this partly accounts for the relatively low monetary values in all strategies. Crown longevity is the sum of the total lifetimes of root canal treated tooth and/or implant supported crowns at that site prior to failure and replacement with a bridge or denture. It is assumed that if no endodontic or implant treatment is provided there will still be a need over the lifetime to fill the space, with a cost consequence [statistically, unfilled anterior spaces are very rare in the UK (Kelly *et al.* 2000)].

The model predicts superior survival of the ISC over a conventional root canal treated tooth with a post-crown based on published evidence. After 20 years around 25% of root canal treated and *re-treated* teeth are predicted to have been lost, whereas 10% of first implants have failed, necessitating a further implant or replacement with a bridge or denture. Despite improved longevity, the implant based strategies still require more interim interventions if a two stage procedure is assumed.

Table 1 Base case results – cost and total crown longevity for each strategy

Strategy	Male age 35 Cost (£)	Male age 35 Longevity	Male age 55 Cost (£)	Male age 55 Longevity	Male age 75 Cost (£)	Male age 75 Longevity
1 (Extraction)	731	0	649	0	540	0
2 (One RoCT)	805	15.81	717	12.62	597	7.1
3 (RoCT then re-treatment)	828	17.29	730	13.56	601	7.41
4 (RoCT then Surgery)	847	17.51	746	13.66	611	7.43
7 (RoCT/re-treatment/Implant)	1071	21.58	916	15.78	694	8
8 (RoCT/Surgery/Implant)	1079	21.59	924	15.78	701	8
5 (RoCT then Implant)	1113	21.47	967	15.73	736	7.99
6 (RoCT/Implant/2nd Implant)	1140	21.85	983	15.88	741	8.02
9 (Implant)	1623	20.12	1570	14.96	1487	7.74
10 (Implant then 2nd Implant)	1717	21.73	1642	15.83	1527	8.01

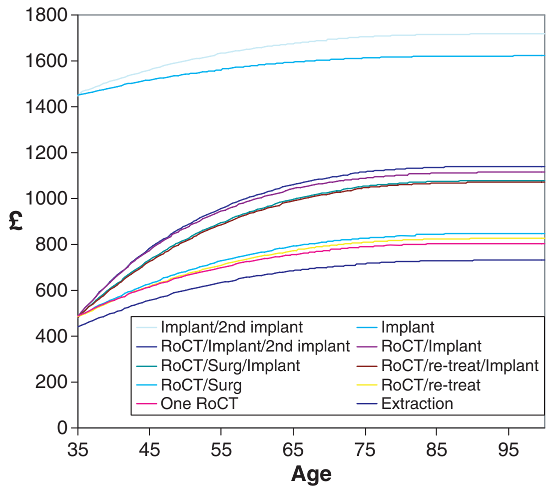

Figure 2 Cumulative costs of each strategy (male age 35 years).

Figure 2 shows the cost accumulation (discounted) for each strategy over 65 years for a male aged 35 years. The significantly greater initial outlay on placing an implant is evident but slightly mitigated by lower ongoing costs, illustrated by the rather shallow curve. The ongoing costs of strategies five (RoCT/Implant) and six (RoCT/Two implants) show the steepest gradient, due to a combination of relatively high failure rates of the first treatment (RoCT), and the high cost of the second treatment (implant).

Cost-effectiveness analysis

The 10 strategies model both the initial intervention and the possible subsequent interventions required to maintain a tooth or prosthesis at that site for the patient's lifetime. To establish cost effectiveness these are ranked in order of cost and their longevity reviewed. When this was done, some strategies were clearly less cost-effective because they have poorer longevity but still cost more than others. They are said to be 'dominated'. Strategies five (RoCT/Implant), nine (One Implant) and 10 (Two Implants) were dominated for patients at all ages analysed (35, 45, 55, 65, 75, 85) and have been excluded.

The remaining strategies are each more effective than less expensive alternatives, but some are significantly more expensive than a comparator but only marginally more effective. It would not make sense to choose such a strategy if, by paying only a little more, we could get a much bigger increase in effectiveness, hence these strategies are excluded (they are said to be 'extendedly dominated'). Both strategies involving a surgical endodontic re-treatment (strategies four and eight) fell in to this category at each age analysed. Whilst surgical endodontic re-treatment has a higher reported success rate than nonsurgical re-treatment in some studies, this has generally followed endodontic re-treatment. The overall increase in longevity, relative to the increased cost, is small. Additional crown years (longevity) can actually be achieved at a lower cost per year with implants.

The results of the cost-effectiveness analysis are shown in Table 2.[1] Strategy 1 (No Treatment) is the least effective and the cheapest, and so this is the comparator for calculating the ICER for strategy two

[1]The costs generated by the model are the expected future costs discounted to the present and not the actual costs faced by a patient if he/she was to receive each of the interventions in the strategy. We would expect many patients to die with an intact root treated tooth, only a proportion will go onto to receive subsequent interventions and the model presents the 'average' costs given the likelihood of failure of restorations undertaken.

Table 2 Incremental cost-effectiveness ratios (ICERs) for non-dominated strategies over the age range 35–85

	ICERs for males aged 35–85 (£)					
Strategy	35	45	55	65	75	85
2 (One RoCT)	5	5	5	6	8	ED
3 (RoCT then re-treatment)	15	15	14	13	11	12
7 (RoCT/re-treatment/Implant)	57	67	84	111	158	241
6 (RoCT/Implant/2nd Implant)	252	383	654	1272	2813	6916

ED-extendedly dominated.

(One RoCT). The comparator for each subsequent strategy is the next best alternative after excluding dominated and extendedly dominated options. All the cost-effective strategies involve initial root treatment. Strategy 2 is expected to cost £5–8 more per year of longevity of the root treated tooth than replacement with a bridge or denture. The table reveals that patients who would choose othograde re-treatment should the root canal treatment fail (strategy three) can expect to extend the longevity of the root treated tooth at a cost per year of additional life of £11–£15 over and above the expected cost if a bridge or denture is fitted on failure of the root treated tooth. Patients who would choose an implant rather than a bridge or denture should the re-treatment fail (strategy 2) can expect to extend the longevity of fixed platform supported crown at a likely additional cost of £57–241 per year.

Sensitivity analysis

When each of the key parameters was altered over the limits of likely variation and the models re-run, the impact on the overall cost-effectiveness of each strategy was small, and no changes in the overall rankings were observed.

General diffusion of implant technology is likely to lead to lower potential component costs and also more efficient provision by general dentists. The impact of halving all of the implant component costs, and re-costing implant procedures at lower professional rates (£50/hour instead of £87/hour) was examined. The impact of a higher wage setting (such as the US) was simulated by costing all procedures using the UK consultant rate (£87/hour) for dentists and by increasing labwork costs by 50%. The impact of a lower wage setting was examined by reducing all wage costs (dentists, assistants and hygienists) to 30% of the UK estimates and by reducing dental laboratory costs by 50%. Costs and ICERs for each scenario for nondominated strategies are presented for a 55-year-old male in Table 3. It can be seen that whilst the absolute effect of higher or lower wage rates on overall costs is marked, the impact on ICERs is small. Unsurprisingly, lowering both wage rates and component costs only for implant procedures leads to a significant reduction in the costs of implant based strategies, but they are still more expensive than conventional treatment. Only when component costs are radically reduced to 10% of the current costs does an implant strategy (strategy five, RoCT/Implant) extendedly dominate an endodontic strategy (strategy three, two RoCTs), in this case for younger males below the age of 37 years.

Discussion

It is unrealistic to expect most dental restorations to last for life (Richardson *et al.* 1999). Although data may be scarce, one systematic review estimated that 50% of all routine dental restorations may be anticipated to last between 10 and 20 years (Downer *et al.* 1999), whilst life-expectancy for women is now currently 80 years or more (http://www.statistics.gov.uk/cci/nugget.asp?id=168). As our urban populations continue to age and expectations of dental function and aesthetics continue to rise, patients, dentists and health planners need to recognize that the next intervention may not be the last, particularly in younger patients. Decisions made at a fixed point in time may set individuals on a pathway with long-term ramifications.

The example considered in this study was a compromised, irreversibly pulpitic maxillary central incisor, with the starting expectation that very few would opt for no treatment at the point of presentation. The immediate choice facing the theoretical patient is whether to preserve the tooth by root canal treatment and a post-retained crown, or whether to have the tooth extracted and replaced with a prosthesis, including the possibility of a single implant. This decision may be influenced by patient and practitioner-based factors, including perceptions of 'success', the special interests of the practitioner, and the attitudes and financial considerations of the patient (Brennan & Spencer 2006, White *et al.* 2006). Debates on the merits of individual treatment decisions are not new and have been recognized clearly at the endodontic/implant interface, where strong arguments have been made on both sides that certain options are more likely to succeed or to be more economic at the point of delivery (Felton 2005, Trope 2005). But debates on 'survival' and immediate costs cannot always account for the lifetime implications, including maintenance and repair, and costs of replacement after outright failure. A decision analytic

Table 3 Impact of varying wages and implant component costs on cost-effectiveness (55 years old)

	Base case		Cheaper implants		Higher wages		Lower wages	
Strategy	Cost (£)	ICER (£)	Cost (£)	ICER (£)	Cost (£)	ICER (£)	Cost (£)	ICER (£)
1 (Extraction)	649		649		993		281	
2 (One RoCT)	717	5	717	5	1088	8	315	3
3 (RoCT then re -treatment)	730	14	730	14	1103	16	321	7
7 (RoC T/re-treatment/Implant)	916	84	822	41	1242	63	451	59
6 (RoCT/Implant/2nd Implant)	983	654	848	254	1286	437	501	486

ICER, incremental cost-effectiveness ratio.

framework combines expected costs and expected benefits in a manner that aids decision making. In the absence of data on patient utility, it was assumed that benefits are proportional to the longevity of a root canal treated tooth or implant; the presentation of ICERs guides the decision according to the value placed on those benefits by the decision maker.

For the clinician, the patient, the commissioner or the policy maker the model reported here gives a reasonably strong guide to the general courses of action that are likely to be the most cost effective in this relatively common scenario. It suggests that root treatment in the first instance is a cost effective strategy, and that the lifetime costs are relatively low, even compared with extraction and replacement with a denture or bridge. Where root treatment fails, in general terms, orthograde re-root treatment is still a reasonably cost effective approach. The lifetime costs are a little higher, but still not a great deal higher, than extraction and bridge or denture placement. Following endodontic re-treatment with surgery was not cost effective in a typical presentation, though this does not rule-out the clinical need for surgery in the event of lesions requiring a biopsy, or the diagnosis of a lesion unlikely to heal by orthograde endodontic means. Implant placement is expensive, and is cost effective in this scenario only after endodontic treatment has failed twice. It is not cost-effective as an initial option. Of course these calculations do not take into account the value that an individual patient may place on any given treatment.

Markov modelling presents a valuable tool for examining such complex lifetime events. Central to the model is a body of survival and outcome data, which informs the probability of a patient remaining in a given health state or moving to a new health state at defined points in time. It allows extrapolation of the clinical data to estimate the expected costs and outcomes over the patient's lifetime. The ICERs combine costs and outcome data in a manner which facilitates rational decision making at the level of the individual, the insurer or the state. It would be easy to misinterpret these findings as some sort of clinical guidance – they are explicitly not that. The model deals in probabilities spread across the generality of patients. Technical or patient issues will tip the balance in favour of one or other approach to treatment for individual patients. However, an understanding of costs and cost effectiveness may help the clinician to advise their patients about the long term costs of any given course of action, or to help insurers or health planners to decide on the basic treatment strategies that give the best value for money. For example, based on this evidence, a reasonable starting point for an insurer may be to provide high quality endodontic treatment, and perhaps to put a premium on high endodontic standards, in the first instance rather than funding implant provision as a first line treatment.

The substantial body of evidence that defined the current model is available in the on-line Appendix S1. The literature was unable to provide the very best quality of evidence on all of the interventions considered, so the model was informed by the best *available* evidence. It is likely that survival of restorations will vary widely according to patient characteristics and the skill of the dentist. The evidence for survival of implants and root treatments was meagre, though of reasonable quality. The weakest evidence related to the survival of partial dentures and bridges. This problem is of course not restricted to Markov modelling, and impacts on any attempt to conduct dental care on a base of evidence. Long-term, prospective clinical trials with large sample sizes and clearly defined outcome criteria are desperately needed (Torabinejad *et al.* 2007).

The costs incorporated within the current model were specific to the state funded healthcare system currently operating in the UK. Clearly salary and labwork costs vary significantly in different countries and the impact on overall strategy costs is large. However, it is the relative costs between strategies rather than the actual values that are important. The relative impact of changing wage costs is surprisingly small. ICERs are changed, but not by an order of magnitude, and overall ranking of strategies remains the same. Hence recommendations based on the calculated ICERs are less susceptible to care costs in different settings. The sensitivity analysis, which demonstrated the stability of the strategy rankings to changes in event probabilities and costs, suggests the findings are robust.

Conclusions

Root canal treatment is an appropriate and cost-effective intervention to extend the life of a maxillary incisor tooth with a diseased pulp. Orthograde re-treatment is also cost-effective, but unless clinically indicated the benefits of additional apical surgery do not justify the additional cost. Increased longevity of the crown can be achieved at a lower cost per year with an implant. At current costs the role of implants is limited to a third line intervention if re-treatment fails.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. A detailed description of the model including all of the data sources used to parameterise it.

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