REVIEW

Tooth survival following non-surgical root canal treatment: a systematic review of the literature

Y.-L. Ng[1], V. Mann[2] & K. Gulabivala[1]

[1]Unit of Endodontology, UCL Eastman Dental Institute, University College London, London; and [2]Department of Medical Statistics, London School of Hygiene and Tropical Medicine, London, UK

Abstract

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Aims To investigate (i) the effect of study characteristics on reported tooth survival after root canal treatment (RCTx) and (ii) the effect of clinical factors on the proportion of root filled teeth surviving after RCTx.

Methodology Longitudinal human clinical studies investigating tooth survival after RCTx which were published up to the end of 2007 were identified electronically (MEDLINE and Cochrane database 1966–2007 December, week 4). In addition, four journals (Dental Traumatology, International Endodontic Journal, Journal of Endodontics, Oral Surgery Oral Medicine Oral Pathology Oral Radiology & Endodontics), bibliographies of all relevant articles and review articles were hand searched. Two reviewers (Y-LN, KG) assessed and selected the studies based on specified inclusion criteria and extracted the data onto a pre-designed proforma, independently. The criteria were as follows: (i) clinical study on RCTx; (ii) stratified analysis of primary and secondary RCTx available; (iii) sample size given and larger than 10; (iv) at least 6-month postoperative review; (v) success based on survival of tooth; and (vi) proportion of teeth surviving after treatment given or could be calculated from the raw data. Three strands of evidence or analyses were used to triangulate a consensus view. The reported findings from individual studies, including those excluded for quantitative analysis, were utilized for the intuitive synthesis, which constituted the first strand of evidence. Secondly, the pooled weighted proportion of teeth surviving and thirdly the combined effects of potential prognostic factors were estimated using the fixed and random effects meta-analyses on studies fulfilling all the inclusion criteria.

Results Of the 31 articles identified, 14 studies published between 1993 and 2007 were included. The majority of studies were retrospective ($n = 10$) and only four prospective. The pooled percentages of reported tooth survival over 2–3, 4–5 and 8–10 years following RCTx were 86% (95% CI: 75%, 98%), 93% (95% CI: 92%, 94%) and 87% (95% CI: 82%, 92%), respectively. Substantial differences in study characteristics were found to hinder effective direct comparison of findings. Evidence for the effect of prognostic factors on tooth survival was weak. Based on the data available for meta-analyses, four conditions were found to significantly improve tooth survival. In descending order of influence, the conditions increasing observed proportion of survival were as follows: (i) a crown restoration after RCTx; (ii) tooth having both mesial and distal proximal contacts; (iii) tooth not functioning as an abutment for removable or fixed prosthesis; and (iv) tooth type or specifically non-molar teeth. Statistical heterogeneity was substantial in some cases but its source could not be investigated because of insufficient available information.

Conclusions The pooled proportion of teeth surviving over 2–10 years following RCTx ranged between 86% and 93%. Four factors (listed above) were identified as significant prognostic factors with concurrence between all three strands of evidence.

Keywords: outcome, root canal treatment, success, survival, systematic review.

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Correspondence: Y-L Ng, Unit of Endodontology, UCL Eastman Dental Institute, UCL, 256 Grays Inn Road, London WC1X 8LD, UK (Tel.: 020 7915 1233; fax: 020 7915 2371; e-mail: p.ng@eastman.ucl.ac.uk).

Introduction

Contemporary root canal treatment procedures aim to eliminate the bacterial biofilm colonizing the complex internal root canal surface. Achievement of this goal is confounded by the size and shape of this space, as mechanical shaping alone is insufficient and chemically active fluids are difficult to deliver effectively to the canal terminus (Gulabivala *et al.* 2005, Nair *et al.* 2005). It has, therefore, been argued that canals should be prepared to larger dimensions (Parris *et al.* 1994, Card *et al.* 2002, Rollison *et al.* 2002) and that chemical agents such as sodium hypochlorite should be used at higher concentrations (Hand *et al.* 1978) and in greater volumes (Lee *et al.* 2004, Huang *et al.* 2008). Larger canal preparations (Sathorn *et al.* 2005a) and more aggressive chemical treatment (Grigoratos *et al.* 2001, Sim *et al.* 2001, Andreasen *et al.* 2002) may, however, weaken dentine and compromise long-term survival of the tooth. The clinical dilemma is one of where to place the emphasis in the contradictory requirements for periapical healing and long-term tooth survival. A balance, therefore, needs to be achieved between conservative techniques favouring tooth survival but possibly worse healing prospects and aggressive techniques favouring the converse combination.

The shift from clinical practice driven by subjective experience, empirical knowledge and authoritative synthesis to one driven by a systematic evidence-based approach (Sackett *et al.* 1996) encourages clinicians and researchers to produce better quality evidence for root canal treatment. This shift has naturally resulted in a surge of systematic reviews on this subject (Hepworth & Friedman 1997, Lewsey *et al.* 2001, Basmadjian-Charles *et al.* 2002, Kojima *et al.* 2004, Paik *et al.* 2004, Sathorn *et al.* 2005b, Schäfer *et al.* 2005, Torabinejad *et al.* 2005, 2007, Del Fabbro *et al.* 2007, Figini *et al.* 2007, Ng *et al.* 2007, 2008a,b, Peng *et al.* 2007, Stavropoulou & Koidis 2007). Classically, the outcome of root canal treatment procedures has been measured by signs and symptoms of periapical healing, consequently most of the published systematic reviews have investigated specific prognostic factors for the resolution of clinical and radiographic signs of periapical disease. The prognostic factors investigated have included the following: vitality of pulps in teeth (Lewsey *et al.* 2001, Kojima *et al.* 2004), periapical status (Basmadjian-Charles *et al.* 2002), apical extent of root filling (Kojima *et al.* 2004, Schäfer *et al.* 2005), number of treatment visits (Sathorn *et al.* 2005b,

Figini *et al.* 2007) and cold lateral versus warm compaction of gutta-percha root fillings (Peng *et al.* 2007). As most of this data were derived from observational studies, the potential for clinical and statistical heterogeneity may be considerable. It was therefore essential for the contribution of study characteristics to the outcome to be explored within a systematic review framework (Ng *et al.* 2007, 2008b). In addition, these reviews did not simply focus on specific individual factors but attempted to investigate the potential interaction between multiple clinical factors. It was found that the statistical heterogeneity could partly be explained by some aspects of study characteristics such as criteria for determination of periapical healing, duration of follow-up, unit of outcome measure, geographical location of the study and year of publication. The significant effect of interactions between preoperative periapical status of the tooth, bacterial culture results and apical extent of root filling on the outcome of treatment were also revealed. However, the effect of potential interaction between the type of treatment and other prognostic factors could not be explored in these systematic reviews because of insufficient data. So far, there are only two systematic reviews of data on root canal retreatment (secondary root canal treatment) (Paik *et al.* 2004, Ng *et al.* 2008b), of which the former only assessed the level of evidence available. In contrast, Ng *et al.* (2008b) adopted the multi-strand approach used in earlier reviews (Ng *et al.* 2007, 2008a).

Lately, data on the high probability of survival of single osseo-integrated dental implants has driven an alternative approach to the management of endodontic problems to the fore, through elective extraction and replacement strategies. The most commonly adopted measure of success for this treatment modality has been survival of the implant fixture; the survival and complications of implant-retained restorations have been less frequently considered (Creugers *et al.* 2000). This shift in treatment planning dynamics prompted a recommendation by the American Association of Endodontists to adopt alternative definitions of success for endodontic treatment, namely, functional survival of the tooth (Friedman & Mor 2004). Since the turn of the millennium, a number of studies (Lazarski *et al.* 2001, Caplan *et al.* 2002, Salehrabi & Rotstein 2004, Stoll *et al.* 2005, Lumley *et al.* 2008) have reported on the survival of teeth (time to extraction) after root canal treatment. Their availability naturally prompted the comparison of outcomes, however inappropriate, between non-surgical root canal treatment and their

competing treatment options (Torabinejad *et al.* 2007). These authors compared the long-term survival, psycho-social and economic outcomes between primary root canal treatment plus restoration, extraction plus replacement with implant-supported prostheses (crowns or bridge) and extraction without tooth replacement. They acknowledged that the lack of comparative studies using similar outcome criteria and time intervals limited the comparisons made. Nevertheless, it was found that root canal treatment plus restoration or tooth extraction plus implant-supported single crown resulted in superior long-term survival compared with tooth extraction plus bridge replacement. Their limited data suggested that extraction without replacement resulted in inferior psycho-social outcomes compared to the other alternatives. The problem of decision-making in the interface of endodontic versus implant replacement has been further reviewed by Zitzmann *et al.* (2009).

At the time of writing this review, the literature on the prognostic factors for tooth survival after non-surgical root canal treatment had not been systematically analysed. Therefore, the aims of this systematic review were to (i) carry out an intuitive critical analysis of the published studies on tooth survival; (ii) estimate the weighted pooled proportion of teeth surviving; and (iii) investigate the effects of various clinical factors on tooth survival; after non-surgical root canal treatment.

Materials and methods

Literature search

Longitudinal clinical studies investigating tooth survival following primary or secondary root canal treatment published up to the end of 2007 were identified electronically (MEDLINE database 1966–2007 December, week 4). Nine key terms were used for the search: (i) root canal treatment; (ii) root canal re-treatment; (iii) root canal therapy; (iv) endodontic treatment; (v) endodontic re-treatment; (vi) endodontics; (vii) treatment outcome; (viii) success; and (ix) survival; with 18 combination strategies (1 AND 7, 1 AND 8, 1 AND 9, 2 AND 7, 2 AND 8, 2 AND 9, 3 AND 7, 3 AND 8, 3 AND 9, 4 AND 7, 4 AND 8, 4 AND 9, 5 AND 7, 5 AND 8, 5 AND 9, 6 AND 7, 6 AND 8, 6 AND 9). A Cochrane Library search was also conducted. In addition, four journals [International Endodontic Journal, Journal of Endodontics, Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics, Dental

Traumatology (& Endodontics)] and bibliographies of all relevant articles and review articles were hand searched. Unpublished studies were identified by searching abstracts and conference proceedings. Personal contacts were also used to identify ongoing or unpublished studies. Full articles were obtained for all relevant titles identified through either electronic or other search methods.

Study selection, quality assessment and data extraction for meta-analyses

Intuitive critical analysis was carried out on all full articles identified through the initial search. Two reviewers (Y-LN, KG) independently assessed and selected the studies for further meta-analyses based on the following inclusion criteria:

1. Clinical study on root canal treatment;
2. Sample size given and larger than 30 teeth;
3. Success based on survival of tooth;
4. At least 6-month postoperative review;
5. Proportion of teeth surviving after treatment given or could be calculated from the raw data.

Disagreements on study inclusion were resolved by discussion. The reasons for study rejection at this or subsequent stages were recorded.

Data were extracted by both reviewers independently using custom-designed data collection forms. The data collection form was piloted on several articles, modified for optimal utility and the final format was agreed between the observers. The extracted and recalculated data could be classified into six groups: proportion of teeth surviving, study characteristics, demographic data of patients, pre-, intra- and postoperative factors. Any disagreement was discussed and data were excluded if agreement could not be reached.

Estimation of pooled proportion of teeth surviving after root canal treatment

The weighted pooled proportion of teeth surviving after treatment was estimated using fixed and random effects meta-analysis with DerSimonean and Laird's methods (Stata version 9.2, College Station, TX, USA). Only those studies that had reported the proportion of tooth survival and its standard error were included for this part of the analysis. The survival data were pooled into three groups based on the duration after treatment when the tooth survival was assessed: 2 or 3 years; 4 or 5 years; and 8, 9 or 10 years.

Estimation of effect of clinical factor on the proportion of teeth surviving

The combined effects (expressed as odds ratio) of clinical factors on tooth survival after treatment were estimated using fixed and random effects meta-analysis with DerSimonean and Laird's methods (Stata version 9.2). Statistical heterogeneity amongst the studies was assessed by Cochran's (*Q*) test (Cochran 1954) using the 10% significance level.

Results

Search results, study selection and data extraction

The literature search for data on the probability of tooth survival following primary or secondary root canal treatment extended up to December 2007. Of the 31 articles identified, 17 were excluded from the meta-analyses. Most were excluded because of the lack of availability of data on tooth survival probability (Molven 1976, Hansen *et al.* 1990, Caplan & Weintraub 1997, Glazer 2000, Mannocci *et al.* 2002, 2005, Nagasiri & Chitmongkolsuk 2005, Willershausen *et al.* 2005, De Backer *et al.* 2006, 2007, Wegner *et al.* 2006, Adolphi *et al.* 2007, Ferrari *et al.* 2007, Miyamoto *et al.* 2007, Piovesan *et al.* 2007). The other two excluded articles consisted of a clinical study on survival of restorations (Kolker *et al.* 2006) and a review article (White *et al.* 2007).

Characteristics of selected studies

The 14 studies investigating the survival of teeth after primary or secondary root canal treatment were published between 1993 and 2007. The majority were retrospective (*n* = 9) and five were prospective cohort studies. The sample size ranged from 50 teeth (Tan *et al.* 2006) to 1 462 936 (Salehrabi & Rotstein 2004) teeth. Drop-out rates were only reported by three studies: 5.2% (Salvi *et al.* 2007); 13.8% (Mackie *et al.* 1993); and 15% (Tilashalski *et al.* 2004). The selected studies were mostly primarily designed to address research questions related to the post-treatment tooth restoration (Table 1); sometimes sub-groups of the overall sample were selected for investigation of specific factors. For example, two studies (Aquilino & Caplan 2002, Caplan *et al.* 2002) had selected two different cohorts based on specified criteria from the original cohort of patients to address two different research questions: (i) effect of crown placement and (ii) effect of

proximal contacts (Table 1). To address the respective research questions, Aquilino & Caplan (2002) excluded teeth with crowns at the point of access, teeth serving as abutments of bridges or teeth without documentation of receiving a definitive restoration, whilst Caplan *et al.* (2002) excluded third molars as well as teeth serving as bridge or over-denture abutments at the point of access or after obturation. Furthermore, Caplan *et al.* (2005) also selected a subset of patients from a prior case–control study (*Caplan & Weintraub 1997) to investigate the prognostic factors for tooth survival after root canal treatment. Most of the selected studies had investigated survival of teeth following *primary root canal treatment* except in two studies (Lynch *et al.* 2004, Stoll *et al.* 2005). Thirteen per cent of the cases in the former study had undergone secondary root canal treatment, whilst the preoperative treatment history of teeth in the latter study was not available.

The effect of prognostic factors on tooth survival after primary or secondary root canal treatment, was investigated by a number of statistical methods including: Pearson χ^2 test to compare proportion of teeth surviving (*n* = 8); log-rank test to compare survival functions (*n* = 1); Cox regression models to compare hazards (*n* = 3); and generalized estimating equations (*n* = 1) to compare odds (Table 1).

Proportions of teeth surviving after root canal treatment

The duration of follow-up after root canal treatment of the tooth ranged from 1 to 11.5 years. Some studies presented cumulative survival functions estimated by life table (Mackie *et al.* 1993) or Kaplan–Meier methods (Aquilino & Caplan 2002, Caplan *et al.* 2002, 2005, Dammaschke *et al.* 2003, Tan *et al.* 2006). The observed proportion of teeth surviving at the end of the follow-up period was also presented in all studies except two (Mackie *et al.* 1993, Caplan *et al.* 2005). The observed proportion of teeth surviving 5 years following treatment was 93% (Alley *et al.* 2004, Chen *et al.* 2007), whilst the proportion surviving 10 years following treatment ranged from 75% (Caplan *et al.* 2002) to 89% (Stoll *et al.* 2005). The estimated pooled proportions of teeth surviving 2 or 3, 4 or 5 and from 8 to 10 years after root canal treatment using meta-analyses were 86.4% (95% CI: 74.7%, 98.1%), 93.3%

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*Studies excluded from meta-analysis.

Table 1 Characteristics of and survival rates reported by the studies selected for meta-analysis (*n* = 14)

Study	Main research question	Study design	No. of teeth	No. of patients	RCTx	Statistical method	Survival rate, %	Duration of follow-up (years)
Mackie *et al.* (1993)	Survival of teeth with immature apex after RCTx	P	93	–	1°	–	86 (E) 86 (E)	5 10
Lazarski *et al.* (2001)	Prevalence and effect of crown and qualification of operator on untoward events after 1°RCTx	R	44 613	–	1°	χ^2	94.4 (O)	2–6
Aquilino & Caplan (2002)	Effect of crown placement (from a pool of 400 teeth)	R	203	156	1°	CR	79.3 (O)	10
Caplan *et al.* (2002)	Effect of number of proximal contacts (from a pool of 400 teeth)	R	221	180	1°	CR	86 (E) 63 (E) 75.1 (O)	5 10 10
Dammaschke *et al.* (2003)	Over 10-year survival of teeth after RCTx	R	190	144	1°	χ^2	85.7 (E) 84.7 (O)	10 10
Alley *et al.* (2004)	Influence of operator	R	350	166	1°	χ^2	93.4 (O)	5
Lynch *et al.* (2004)	Effect of type of coronal restoration	R	176	166	?	χ^2	78.4 (O)	1–5 (mean = 3)
Salehrabi & Rotstein (2004)	Tooth retention over 8 years after RCTx	R	1 462 936	–	1°	χ^2	97.1 (O)	8
Tilashalski *et al.* (2004)	Outcome of endodontic treatment	P	75	–	1°	GEE	81 (O)	4
Caplan *et al.* (2005)	8-year survival of teeth with RCTx and teeth without RCTx (original pool = 1795 teeth/patients)	C-C (R)	202 matched pair of teeth	202	1°	CR	94 (E) 89.5 (E)	4 8
Stoll *et al.* (2005)	Prognostic factors for survival of root-treated tooth (*retreatment or extraction of the root-treated tooth were considered as failure*)	R	914	–	[a]1°/2°	LR	74 (E) 88.5 (O)	10
Tan *et al.* (2006)	Survival of cracked teeth after RCTx	P	50	49	1°	χ^2	85.5 (O)	2
Chen *et al.* (2007)	Tooth retention and untoward events over 5 years after RCTx	R	1 557 547	–	1°	χ^2	93.2 (O)	5
Salvi *et al.* (2007)	Effect of post placement in teeth after RCTx	P	308	166	1°	χ^2	93.8 (O)	2.1–11.5 (mean 5.3)

C-C, case-control study; P, prospective study; R, Retrospective study; RCTx, Root canal treatment (1° = primary; 2° = secondary; ? = unknown); Statistical tests investigating influencing factors: CR, Cox regression; GEE, Generalized estimating equations; χ^2, Chi-square test; LR, log-rank test; –, influencing factors not investigated; E, Estimated cumulative survival function; O, Observed proportion of teeth surviving.
[a]Thirteen per cent of cases had undergone 2°RCT.

(95% CI: 92.0%, 94.4%) and 86.7% (95% CI: 81.6%, 91.8%), respectively (Figs 1–3).

Extraction was more frequently instituted than surgical or non-surgical retreatment when primary root canal treatment was deemed to have failed (Salehrabi & Rotstein 2004, Chen *et al.* 2007). The former study found that most extractions were undertaken within 3 years after root canal treatment but a similar number of extractions were also undertaken over the 5- or 10-year period in the latter study. Of those teeth surviving following treatment, only a small proportion had undergone further non-surgical (0.31–2.47%) or surgical re-treatment (0.45–1.41%) (Lazarski *et al.* 2001, Salehrabi & Rotstein 2004). Surgical re-treatments were carried out more frequently on anterior teeth when compared with premolar or molar teeth (Lazarski *et al.* 2001, Salehrabi & Rotstein 2004).
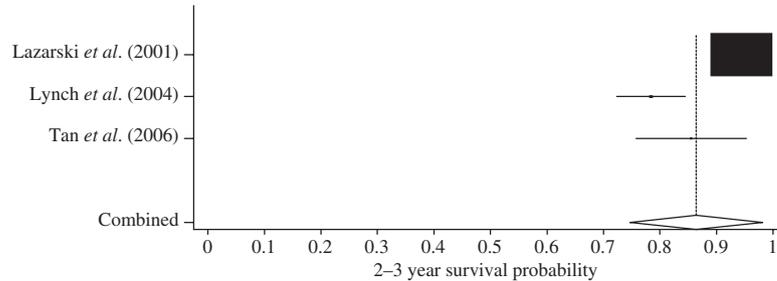

Figure 1 Results of meta-analysis. The estimated proportion of teeth surviving and 95% confidence interval (CI) are shown for each study. The overall estimated 2–3 year proportion of teeth surviving after root canal treatment was 86.4% (95% CI 74.7%, 98.1%) and is indicated by the dotted line.
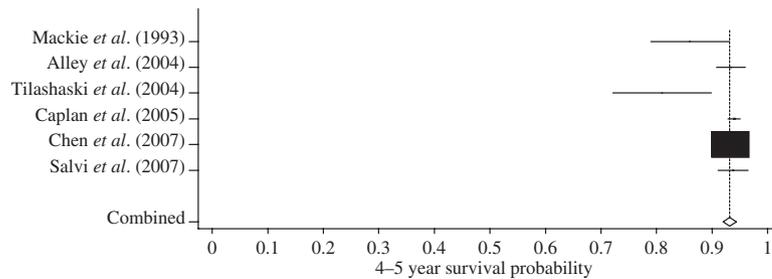

Figure 2 Results of meta-analysis. The estimated proportion of teeth surviving and 95% confidence interval (CI) are shown for each study. The over estimated 4–5 year proportion of teeth surviving after root canal treatment was 93.3% (95% CI: 92.0%, 94.4%) and is indicated by the dotted line.
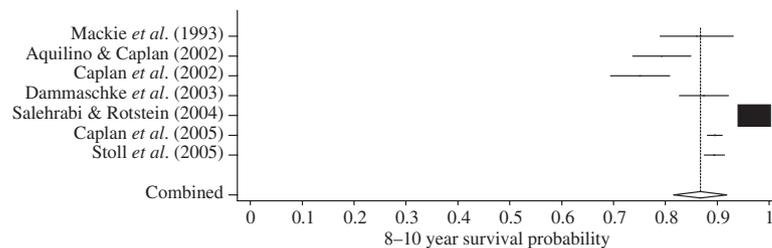

Figure 3 Results of meta-analysis. The estimated proportion of teeth surviving and 95% confidence interval (CI) are shown for each study. The over estimated 8–10 year proportion of teeth surviving after root canal treatment was 86.7% (95% CI; 81.6%, 91.8%) and is indicated by the dotted line.

Prognostic factors for proportion of teeth surviving after non-surgical root canal treatment

The prognostic factors investigated could be classified into general patient factors; preoperative tooth factors; intra-operative factors; and post root canal treatment restorative factors (Table 2). The most frequently investigated were type and location of the tooth ($n = 8$) followed by type of coronal restoration ($n = 6$), presence and type of post ($n = 5$), qualification of operator ($n = 4$), gender of patient ($n = 4$) and extent and quality of root filling ($n = 4$). Table 2 shows an absence of systematic evaluation of potential prognostic factors by virtue of the number of empty cells. Comprehensive evaluation of more than a few factors was undertaken by only a small number of studies.

General and preoperative prognostic factors

Qualification of operators

One retrospective study that was specifically designed to investigate the effect of operators found that teeth with treatment carried out by specialist Endodontists were associated with a higher probability of tooth survival over 5 years than those treated by generalists (98.1% vs. 89.7%, respectively) (Alley *et al.* 2004). Whereas Lazarski *et al.* (2001), in a large retrospective study with 44 613 cases, only found that those cases undergoing additional surgical endodontic treatment by endodontists were associated with a significantly higher chance of survival. This was contrary to the findings of others (*Caplan & Weintraub 1997, Stoll *et al.* 2005). The former (*Caplan & Weintraub's 1997) case–control study (96 extracted teeth, 117 surviving teeth) had a rather small sample size, whereas the latter study (Stoll *et al.* 2005) considered competing outcomes (subsequent replacement of root filling, periradicular surgery and tooth extraction were considered as failure) and found no difference in the survival of root fillings completed by qualified dentists or dental students.

Three studies (Lazarski *et al.* 2001, Alley *et al.* 2004, Tilashalski *et al.* 2004) had provided tooth survival data on treatment carried out by generalists and endodontists. The data from these three studies were pooled for meta-analysis. The teeth treated by general dental practitioners were found to be associated with a slightly lower probability of survival (OR = 0.91; 95% CI 0.23, 3.66) but the difference was not significant (Fig. 4). A substantial heterogeneity ($Q = 12$, degree of freedom = 2, $P = 0.003$) was found amongst these studies.

Gender, age, medical status and ethnic origin of patient

None of the previous studies had found any significant association between survival of teeth after root canal treatment and gender of the patient (*Caplan & Weintraub 1997, Lazarski *et al.* 2001, Caplan *et al.* 2002, Dammaschke *et al.* 2003, Tan *et al.* 2006).

The tooth survival probabilities by gender were provided by three studies (Lazarski *et al.* 2001, Caplan *et al.* 2002, Tan *et al.* 2006). Caplan *et al.* (2002) presented both 5-year and 10-year survival probabilities; the 5-year survival data were used for meta-analysis because the other two studies only followed the cases up to 6 years. The result showed a slightly lower proportion of tooth survival for male patients after root canal treatment (OR = 0.97; 95% CI 0.88, 1.06) compared to female patients, although the difference was not significant (Fig. 5). The heterogeneity 2.7 (2 df) was also not significant.

Tooth extraction following root canal treatment, for both genders, was found to increase by 1–2% for each decade of the patient's age, reaching a plateau after age 60 (Lazarski *et al.* 2001). In concurrence with this finding, *Caplan & Weintraub (1997) dichotomized patients' age at 50 years and found that the older age group was associated with a significantly greater loss of teeth following root canal treatment. Using much smaller sample sizes, other studies had not found statistically significant differences in tooth survival by age (Aquilino & Caplan 2002, Dammaschke *et al.* 2003, *Nagasiri & Chitmongkolsuk 2005). These studies had categorized the continuous age variable into 3 (Aquilino & Caplan 2002) or 4 (Dammaschke *et al.* 2003) bands, rendering direct comparison of results impossible. Only Aquilino & Caplan (2002) presented the observed proportion of teeth surviving after treatment by this factor. They categorized age into three groups: 54 years or younger, 55–64 years old and 65 years or older. The corresponding 5-year proportions of survival were 93% (95% CI: 87%, 98%), 87% (95% CI: 79%, 96%) and 82% (95% CI: 72%, 92%), respectively. In contrast, the 10-year survival rates were 82% (95% CI: 74%, 90%), 84% (95% CI: 75%, 93%) and 69% (95% CI: 57%, 81%), respectively.

Only one study, based in Singapore, had investigated the influence of ethnic origin (Chinese, Indian, others) of patients on survival of root filled cracked teeth; they found no significant effect because of this factor (Tan *et al.* 2006). However, the number of patients of Indian (5/49) and other (3/49) origins were too small for valid statistical analyses. The proportions of teeth surviving

Table 2 Prognostic factors investigated in selected studies

Factors	Mackie et al. (1993)	Lazarski et al. (2001)	Aquilino & Caplan (2002)	Caplan et al. (2002)	Dammaschke et al. (2003)	Alley et al. (2004)	Lynch et al. (2004)	Salehrabi & Rotstein (2004)	Tilashalski et al. (2004)	Caplan et al. (2005)	Stoll et al. (2005)	Tan et al. (2006)	Chen et al. (2007)	Salvi et al. (2007)	[a]Total
Qualification of operator	×	×							×		×				4
Sex	×			☒	☒							×			4
Age		☑	×		×										3
Ethic origin												×			1
Medical condition			×												1
Tooth type and location	✔	✔	✔	✔	☒	?		?		☑		✔	✔		8
Preoperative pain					✔										1
Pulpal status											✔				1
Periapical status			×		✔						✔				3
1°RCT vs. 2°RCT				×							☒				2
Preoperative pocket												✔			1
Preoperative cracks												✔			1
RF extent and quality				×	☑	✔					✔				4
Duration between root filling and restoration			×												1
Proximal contacts			×	✔											2
Type of restoration	?	?	✔	✔	✔	?	✔	✔						×	6
Type of core				×		?									1
Presence and type of post	✔	✔			×	?		☒						×	5
Abutment	✔	✔												?	2

1°RCT, primary root canal treatment; 2°RCT, secondary root canal treatment; RF, root filling.
✔ = identified as significant factor and data available; ☑ = significant factor but data not available; × = identified as significant factor but data not available; ☒ = insignificant factor but data not available; ☑ = identified as insignificant factor and data available; ? = data available but effect was not investigated; empty box = factor not investigated and data not available.
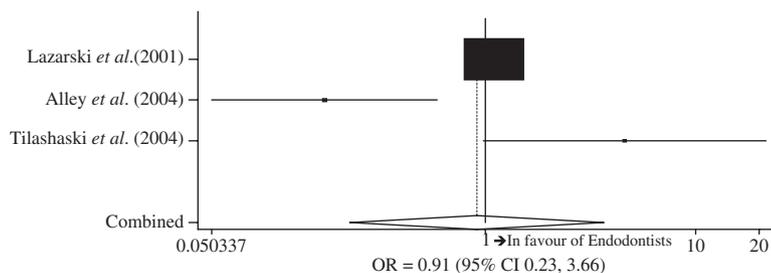[a]Total number of studies that had investigated the respective factor.

Figure 4 Results of meta-analysis comparing proportion of teeth surviving following treatment by endodontists and non-endodontists. The overall estimated odds ratio was 0.91 (95% CI: 0.23, 3.66) and is indicated by the dotted line.
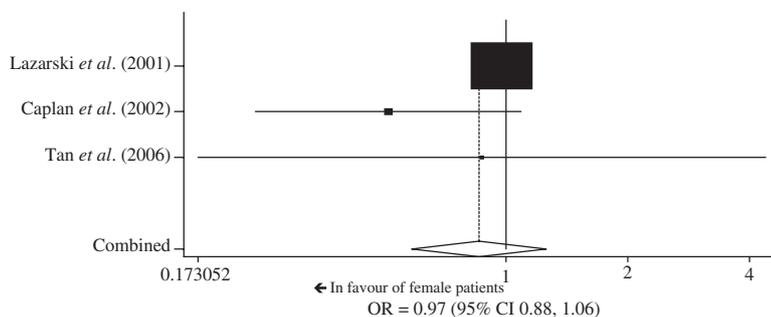

Figure 5 Results of meta-analysis comparing proportion of teeth surviving in male and female patients. The overall estimated odds ratio was 0.97 (95% CI: 0.88, 1.06) and is indicated by the dotted line.

over 2 years after root canal treatment in patients of Chinese, Indian and other origin were 83% (95% CI: 72%, 95%), 100% and 100%, respectively.

Amongst the many medical conditions afflicting such patient groups, only diabetes and hypertension had been investigated for their effect on loss of root-treated teeth; they were indeed found to be associated with a higher chance of tooth loss (*Mindiola *et al.* 2006). Using a much smaller sample size, Caplan *et al.* (2002) found no difference in tooth survival after primary treatment between patients who required medication for hypertension/heart disease and those not requiring such medication. Stratified data on tooth survival by medical conditions of patients had only been presented by Caplan *et al.* (2002). The reported 5-year proportions of teeth surviving in patients receiving medication for heart disease/hypertension and those not receiving such medication were 82% (95% CI: 69%, 95%) and 65% (95% CI: 47%, 80%), respectively, whereas the 10-year survival rates were 86% (95% CI: 81%, 91%) and 63% (95% CI: 56%, 70%), respectively.

The effects of patient's gender, ethnic origin and medical condition were not estimated using meta-analysis because of insufficient data.

Location and type of tooth

The interpretation of previous findings on the effect of tooth type and location on tooth survival following root canal treatment was complicated by the diverse approach in stratifying tooth type for analysis. Those studies which had included all tooth types tended to stratify them into anterior (front), premolar and molar teeth (Lazarski *et al.* 2001, Dammaschke *et al.* 2003, Salehrabi & Rotstein 2004, Chen *et al.* 2007). Some authors further stratified anterior teeth into incisors and canines (Caplan *et al.* 2002, Salvi *et al.* 2007). Molar teeth have been stratified further into maxillary and mandibular (Salvi *et al.* 2007); first and second (Caplan *et al.* 2002); and first, second and third (Alley *et al.* 2004) molar types. Tan *et al.* (2006) only included premolar and molar teeth with cracks; in addition to comparing premolar and molar teeth, they also compared tooth survival between the maxillary and mandibular arches. The studies by Caplan's group focusing their investigation on molar teeth, stratified them into second-molars and non-second-molars (Aquilino & Caplan 2002); or molars and non-molars (Caplan *et al.* 2005).

Regardless of categorization, second molar teeth (Aquilino & Caplan 2002, Caplan *et al.* 2002), molar

teeth (Caplan *et al.* 2005) or posterior teeth (Lazarski *et al.* 2001) were associated with a lower chance of survival after root canal treatment, which was in contrast to the findings of other studies (*Caplan & Weintraub 1997, Dammaschke *et al.* 2003, Tan *et al.* 2006). The latter studies including relatively small sample sizes, failed to dichotomize the molar teeth (first or second) and did not find any significant influence by tooth type. Location of teeth in the maxillary or mandibular arches made no difference to the probabilities of tooth survival (Dammaschke *et al.* 2003, Tan *et al.* 2006).

Eight studies (Lazarski *et al.* 2001, Aquilino & Caplan 2002, Caplan *et al.* 2002, Alley *et al.* 2004, Salehrabi & Rotstein 2004, Tan *et al.* 2006, Chen *et al.* 2007, Salvi *et al.* 2007) presented data on proportions of anterior, premolar and molar teeth surviving after root canal treatment. The data from Caplan *et al.* (2002) were excluded because their study cohort was selected from the same patient pool as Aquilino & Caplan (2002). There was no loss of anterior teeth after root canal treatment in the study by Salvi *et al.* (2007); therefore, they could not be included in these analyses, whilst Tan *et al.* (2006) had not included anterior teeth in their study sample. The results from meta-analyses revealed that the survival probability of anterior teeth was higher than that of premolar (OR = 1.29; 95% CI 0.91, 1.84) or molar (OR = 1.28; 0.91, 1.82) teeth, although the differences were not significant (Table 3). However, premolar teeth were associated with significantly higher survival proportions (OR = 1.19; 95% CI 1.01, 1.41) than molar teeth. To include data from more studies, the data for anterior and premolar teeth were pooled into a non-molar category for further analysis. This revealed that non-molar teeth were associated with significantly higher survival proportions (OR = 1.26; 95% CI 1.00, 1.58) than molar teeth (Table 3). All the above-mentioned analyses showed statistically significant heterogeneity amongst the studies.

Remaining tooth structure and presence of crack(s)
Root canal treatment should only be carried out if the restorability of the tooth has been ascertained (Gulabivala 2004). At present, no restorability criteria

validated by long-term outcome data are available to guide clinicians in assessing the survival prognosis by tooth restorability.

The survival of teeth with cracks prior to primary treatment has been specifically investigated in one prospective study (Tan *et al.* 2006). A large proportion (85.5%) of these teeth survived for at least 2 years following root canal treatment. Tooth survival was influenced by the number of preoperative cracks but not by their location and extension. The teeth were either restored with a crown or an amalgam core with an orthodontic band for protection. The results of the authors' original analyses are presented in Table 4, but the data should be interpreted with caution because of the small sample size.

Pulpal and periapical status
Amongst the preoperative conditions of teeth, the effects of pulpal and periapical status, pain experience and previous root canal treatment on tooth survival have been investigated.

Teeth with vital pulps (Stoll *et al.* 2005), absence of periapical lesions (Dammaschke *et al.* 2003, Stoll *et al.* 2005) or absence of pain (Stoll *et al.* 2005) prior to root canal treatment were associated with significantly longer survival times or a higher chance of survival than their counterparts after 10 years postoperatively. Aquilino & Caplan (2002) found a 7% difference in the proportion of surviving teeth with or without preoperative periapical lesions, although the difference was not significant; a finding which could be attributed to the small proportion (26%) of teeth with preoperative lesions. In contrast to Stoll *et al.* (2005), *Caplan & Weintraub (1997) found no difference in the prevalence of preoperative pain between extracted and surviving teeth in a case–control study. The discrepancy may be attributed to the fact that the former study had a larger sample size and defined failure event as teeth undergoing subsequent non-surgical or surgical treatments in addition to tooth extraction (Stoll *et al.* 2005).

Tooth survival data by preoperative pulpal status and pain were only available in the study by Stoll *et al.* (2005). They reported that the 10-year proportion of

Comparisons (test versus reference categories)	No. of studies	Odds ratio	95% CI	Heterogeneity	
				χ^2 value	*P* value
Anterior versus premolar teeth	5	1.29	0.91, 1.84	763.9	<0.001
Anterior versus molar teeth	5	1.28	0.91, 1.82	1058.8	<0.001
Premolar versus molar teeth	7	1.19	1.01, 1.41	245.4	<0.001
Non-molar versus molar teeth	7	1.26	1.00, 1.58	799.8	<0.001

Table 3 The effect of tooth type on proportion of teeth surviving obtained from random effects meta-analyses

Table 4 Results of analyses by Tan *et al.* (2006)

Prognostic factors (test versus reference categories)	Odds ratio	95% CI
Location of cracks		
Mesial versus not	1.4	0.4, 5.4
Distal versus not	No loss of teeth with distal cracks	
Buccal versus not	0.9	0.1, 4.3
Palatal or lingual versus not	1.8	0.5, 6.2
Multiplicity of cracks		
Multiple versus single	No loss of teeth with single crack	
Extension of cracks		
Radicular extension versus within crown	2.5	0.6, 8.2
Preoperative pocket		
Present versus absence	4.9	1.2, 2.0

survival for teeth with vital pulps and teeth with non-vital pulps was 81% and 68%, respectively. In contrast, the proportion of teeth surviving with or without preoperative pain, was 67% and 79%, respectively.

Three studies (Aquilino & Caplan 2002, Dammaschke *et al.* 2003, Stoll *et al.* 2005) had provided tooth survival data by preoperative periapical status. Meta-analysis revealed that teeth without a periapical lesion were associated with a significantly higher chance of survival than those with a preoperative periapical lesion (OR = 2.40; 95% CI 1.11, 5.18) (Fig. 6); with substantial heterogeneity 7.6 (2 df). The study by Stoll *et al.* (2005) had included competing outcomes other than tooth survival, such as root canal re-treatment. The meta-analysis was therefore repeated by excluding this study to reveal a smaller and now insignificant influence because of this factor (OR = 1.62; 95% CI 0.96, 2.73).

Given that the survival of teeth with previous root canal treatment might be worse as they had already failed in one sense or were destined to fail, Caplan *et al.* (2002) limited their analysis to teeth undergoing primary root canal treatment. Contrary to the above-mentioned speculation, Stoll *et al.* (2005) reported no significant difference in the survival time of teeth following primary or secondary root canal treatment. They did, however, point out that only 13% of the teeth had undergone secondary treatment.

Intra-operative prognostic factors

Of all the potential intra-operative factors, only the effects of apical extent and quality of root filling on tooth survival have been investigated.
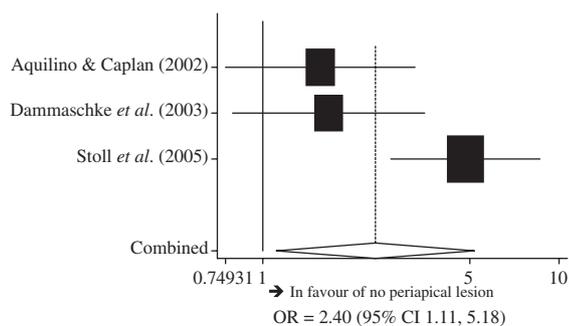

Figure 6 Results of meta-analysis comparing proportion of teeth surviving in the absence or presence of preoperative periapical lesion. The overall estimated odds ratio was 2.40 (95% CI: 1.11, 5.18) and is indicated by the dotted line.

Apical extent of root filling

As per the findings on periapical healing as the outcome measure (Ng *et al.* 2008a), teeth with root fillings that were flush (Dammaschke *et al.* 2003, Alley *et al.* 2004, Stoll *et al.* 2005) or slightly short (Dammaschke *et al.* 2003) of the radiographic apex were associated with a significantly higher probability of survival after 5 and 10 years. Whilst *Caplan & Weintraub (1997) observed similar trends, their findings were not statistically significant. In their case–control study, the proportion of long root fillings was higher amongst extracted teeth (31%) than amongst surviving teeth (24%). Whereas the proportion of short root fillings was lower amongst the extracted (15%) than the surviving (19%) teeth.

Only two studies (Alley *et al.* 2004, Stoll *et al.* 2005) presented tooth survival data by apical extent of root filling. The weighted pooled survival rates for short, flush and long root fillings are presented in Table 5. Teeth with flush root fillings were associated with a significantly higher survival probability (OR = 4.70, 95% CI 2.98, 7.41) than teeth with short root fillings. The heterogeneity 1.4 (1 df) (P = 0.2) was

Table 5 Pooled estimates of percentage of teeth surviving by apical extent of root fillings

Extent of root filling	Number of studies	Number of teeth	Weighted pooled survival rate (95% CI)
Short	2	211	80.9% (68.0%, 93.9%)
Flush	2	837	94.6% (93.0%, 96.1%)
[a]Long	1	117	[a]74.0% (65.6%, 82.5%)

[a]Data from Alley *et al.* (2004) were excluded because there was no loss of teeth in this category. The results reported by Stoll *et al.* (2005) are presented in this table.

not significant. Data from Alley *et al.* (2004) on long root filling had to be excluded as they reported no loss of teeth in this category. Therefore, there was insufficient data for further meta-analysis to compare the survival of teeth with long root fillings against those with short or flush root fillings.

Quality of root filling

Reports on the effect of quality of root fillings on tooth survival have been conflicting. Using survival of root filling as an outcome measure, including extraction of the tooth, replacement of the root filling or periradicular surgery as failure events, Stoll *et al.* (2005) found a significant effect from quality of root fillings.

Using loss of the root-treated tooth as the sole outcome measure, Caplan *et al.* (2002) found that root fillings with voids or 'poor quality' had no significant influence on the tooth survival. The number and proportion of cases with voids in their root fillings was small in their study (28/216). In an earlier study by the same group, this factor was not eligible for the final multi-variable analyses because there was a >90/10 split in the frequency between root fillings without (95.4%) and with voids (4.6%) (*Caplan & Weintraub 1997). The 5- and 10-year estimated percentage of teeth surviving after root canal treatments reported by Caplan *et al.* (2002) were: 85% (95% CI: 80%, 90%) and 62% (95% CI: 55%, 69%), respectively, for teeth without voids in the root fillings ($n = 188$ teeth); and 86% (95% CI: 73%, 99%) and 68% (95% CI: 51%, 85%), respectively, for teeth with voids in the root fillings ($n = 28$ teeth). Meta-analysis could not be performed because of insufficient data.

Postoperative prognostic factors

Type of coronal restoration

A larger proportion of root-treated teeth survived if they were permanently restored within ninety days following root canal treatment (*Mindiola *et al.* 2006). Teeth restored with a permanent restoration (Lazarski *et al.* 2001, Dammaschke *et al.* 2003, Lynch *et al.* 2004) or crown (Lazarski *et al.* 2001, Aquilino & Caplan 2002, Caplan *et al.* 2002, Salehrabi & Rotstein 2004) were associated with significantly higher survival than their counterparts. These findings were corroborated by a recent systematic review (Stavropoulou & Koidis 2007). Their systematic review has also considered fracture of the tooth, fracture of the restoration, post fracture, post decementation, dislodgment of the restoration and marginal leakage of the restoration in addition to extraction as treatment failure. They found 10-year survival for crowned-teeth to be 81% (SD = ±12%), which was higher than the 63% (SD = ±15%) for teeth restored with a direct restoration (resin composites, amalgam, cements). Unfortunately, the analyses could not be stratified by tooth type. Although the authors had quite rightly pointed out the difficulties in undertaking meta-analysis on retrospective data as the study characteristics or reporting methodology were not standardized, the degree of statistical heterogeneity were not explored.

Four studies (Lazarski *et al.* 2001, Aquilino & Caplan 2002, Alley *et al.* 2004, Lynch *et al.* 2004) had provided the proportion of teeth surviving when restored with or without a crown after root canal treatment. Those teeth restored with a crown were associated with a significantly higher survival probability (OR = 3.92; 95% CI 3.54, 4.33) than those without a crown after root canal treatment (Table 6). Unfortunately, survival data were only stratified by anterior and posterior teeth in one study (Lynch *et al.* 2004); therefore, subgroup meta-analysis by tooth type was not feasible.

Of the teeth restored with plastic restorations, those restored with composite, amalgam or temporary cement had similar 10-year survival probabilities (Dammaschke *et al.* 2003). There was insufficient data

Comparisons (test versus reference categories)	No. of studies	Odds ratio	95% CI	Heterogeneity	
				χ^2 value	P value
Restoration with crown (yes versus no)	4	3.92	3.54, 4.33	0.5	0.9
Restoration retained with post (yes versus no)	5	0.89	0.75, 1.05	16.5	0.002
Functioned as fixed-prosthesis abutment (no versus yes)	3	1.70	1.31, 2.20	3.23	0.2
Number of proximal contacts (2 vs. 1 or 0)	2	3.08	1.78, 5.32	0.99	0.3

Table 6 The effect of the restorative status of teeth after treatment obtained from random effects meta-analyses

to compare by meta-analyses, the survival of root-treated teeth restored with different plastic restorative materials.

Of those teeth restored with a crown, the time between root filling and core placement (Aquilino & Caplan 2002) as well as the use of post retention (*Caplan & Weintraub 1997, Aquilino & Caplan 2002, Caplan *et al.* 2002, Salehrabi & Rotstein 2004) had no significant influence on tooth survival. In contrast, Lazarski *et al.* (2001) reported that teeth with prefabricated posts had a higher chance of survival than those with cast post and cores. Survival data by presence of post were provided by five studies (Lazarski *et al.* 2001, Aquilino & Caplan 2002, Dammaschke *et al.* 2003, Alley *et al.* 2004, Salvi *et al.* 2007). Meta-analysis revealed that the proportion of teeth with post-retained restorations surviving was slightly lower (OR = 0.89; 95% CI 0.75, 1.05) than that of teeth without a post-retained restoration after root canal treatment, although the difference was statistically insignificant (Table 6). The heterogeneity amongst studies was substantial.

Teeth with single unit crowns were found to have a higher chance of survival than those used as a bridge (Lazarski *et al.* 2001) or denture (Alley *et al.* 2004) abutment. Furthermore, root-treated teeth used as bridge abutments had a lower chance of survival than those used as denture abutments (Alley *et al.* 2004). In stark contrast, *Wegner *et al.* (2006) reported higher failures for removable prostheses abutments compared to those used as fixed prostheses abutments. The discrepancy might be attributed to the fact that in the latter study, all the prostheses were post retained, made within the department, and the failure of the post and fracture of the tooth were also considered as failure events. Meta-analysis of data from three studies (Lazarski *et al.* 2001, Alley *et al.* 2004, Salvi *et al.* 2007) showed that teeth *not* functioning as fixed or removable prosthesis abutments were associated with a significantly higher survival probability than those that functioned as fixed-prosthesis abutments (OR = 1.70; 95% CI 1.31, 2.20) (Table 6).

Number of proximal contacts
The number of proximal contacts may influence the distribution of occlusal loading on a tooth. Root-treated teeth with two proximal contacts were found to be associated with a higher chance of survival after root canal treatment (*Caplan & Weintraub 1997, Caplan *et al.* 2002). Aquilino & Caplan (2002) found the same association but they did not include this factor in their final Cox regression model to investigate the effect of crown placement; this was because of confounding between the two variables: crown placement and proximal contacts. Curiously, in their other study (Caplan *et al.* 2002) aiming to investigate the effect of proximal contacts, both explanatory factors (crowned-teeth and two proximal contacts) were entered in the final model and proved to be significant at the 1% level. The reported effect of 'crowned-teeth' [Hazard Ratio = 13.6 (7.1, 26.1)] was more profound, although with a very wide confidence interval, than the effect of 'two proximal contacts' [Hazard Ratio = 3.1 (1.9, 5.1)]. The fact that terminal molar teeth would have a maximum of one proximal contact might render investigation of this factor problematic. Root-treated terminal teeth with preoperative cracks were found to have a lower chance of 2-year survival than non-terminal teeth (Tan *et al.* 2006).

Only two studies (Aquilino & Caplan 2002, Alley *et al.* 2004) had provided the proportion of teeth surviving by the number of proximal contacts. Teeth with both mesial and distal adjacent teeth (two proximal contacts) were associated with a significantly higher survival probability (OR = 3.08; 95% CI 1.78, 5.32) than those with one or more missing adjacent teeth (Table 6).

Discussion

The number of studies investigating the outcome measure 'survival of teeth' after root canal treatment was far fewer than those on the measure of 'periapical healing' (Ng *et al.* 2007, 2008b). Only 31 studies on tooth survival after primary root canal treatment had been published up to the end of 2007 whilst none had specifically investigated tooth survival after secondary root canal treatment. Most of the studies primarily aimed to investigate the survival of the restoration rather than the root-treated tooth. Survival of root-treated teeth, *per se*, began to draw the attention of endodontic researchers when the treatment planning challenge posed by the putative 'predictability' of the alternative treatment of implant-retained single unit restorations gained ground (Naert *et al.* 2002); hence, the absence of such published studies prior to 2000.

Consistent with the studies on periapical healing, most research on tooth survival could be classified under retrospective cohort studies. They were mostly designed to answer different clinical questions, some focussing on the survival of the restoration and others on the restoration and tooth. The sample size ranged

from 50 (Tan *et al.* 2006) to 1 462 936 (Salehrabi & Rotstein 2004) teeth, a much broader range than studies on periapical healing (Ng *et al.* 2007, 2008b). The former (Tan *et al.* 2006) was a prospective study investigating the survival of teeth with cracks and root canal treatment, whilst the latter (Salehrabi & Rotstein 2004) was a large epidemiological retrospective study based on insurance company data. The insurance company had a profile of insuring approximately 14 million individuals in 50 states across the USA. Although a very large patient cohort could be recruited from those on private or national insurance plans (Lazarski *et al.* 2001, Salehrabi & Rotstein 2004, Chen *et al.* 2007, Lumley *et al.* 2008), the accuracy and extent of recorded details for investigation of prognostic factors is usually compromised. The potential influencing factors analysed in these studies were unfortunately limited by those available on the insurance institution database. The study by Lumley *et al.* (2008) was based in the UK and published beyond the time frame of the present review. Unlike the other studies, they investigated the survival of root fillings placed by general dental practitioners working within the UK National Health Service (NHS) contract. The sample size (30 843 teeth) was large but the data on outcome as well as potential prognostic factors were only obtained from the database containing payment claims submitted by dentists upon treatment completion. Failure of a root filling was defined by one of the following events: extraction of the tooth, replacement of the root filling or periradicular surgery performed on the tooth. They found 74% of the sample teeth to survive without further intervention in the root canal within 10 years following the initial root canal treatment. Survival of root fillings was found to be strongly associated with the age and treatment history of the patient. However, the pre- and intra-operative condition of the teeth studied or the possibility of patients seeking further treatment elsewhere privately following the root canal treatment by the NHS dentist were not accounted for in their analyses. Using a similar outcome measure, another UK-based study (Tickle *et al.* 2008) on root canal treatment performed by general dental practitioners ($n = 12$) working under the NHS scheme, managed to recruit a smaller patient cohort with limited tooth sample (174 mandibular first permanent molars). They did, however, examine each patient's clinical notes and post-operative periapical radiographs and found that most failure events were tooth extraction ($n = 16$) with only one root filling being replaced following root canal treatment within the period of

study (3–8 years post-operatively). The survival of teeth/root filling was found to be significantly better for teeth restored with a crown rather than a plastic restoration, but the quality of root filling had no significant effect. Unfortunately, once again, the potential confounders had not been considered. The restorations had been placed by the same dentist providing the root canal treatment. Clinically, the endodontic as well as restorative prognoses of the tooth judged by the dentist may potentially influence the type of restoration being placed. Both the dentist and patient are less likely to consent to a permanent crown on a tooth associated with persistent problems following root canal treatment or on a tooth judged to have a guarded prognosis. It may be argued that the speculation is supported by the fact that none of the teeth restored with a crown failed. Furthermore, their finding on the insignificant influence from quality of root filling may have been biased by the 36% of root fillings which proved un-assessable because the radiographs were unreadable. Interestingly, none of the large epidemiological studies (Lazarski *et al.* 2001, Salehrabi & Rotstein 2004, Chen *et al.* 2007, Lumley *et al.* 2008) reported the drop-out rates of their sample population.

In the present review, the estimation of the weighted pooled proportion of survival was complicated by the substantial variations in the duration of follow-up, consistent with the findings by Torabinejad *et al.* (2007). They had, therefore, partitioned previous data on proportion of tooth survival for the purposes of analysis into periods between 2–6 years and those lasting more than 6 years. The present review with more studies included for meta-analysis, adopted a different strategy aimed to reduce the statistical heterogeneity by partitioning the data with narrower time intervals (2–3, 4–5, 8–10 years). The weighted pooled percentages of teeth surviving after root canal treatment over 2–10 years (86–93%) were lower than the 94–97% reported by Torabinejad *et al.* (2007). The difference could be attributable to the different number of studies included and the strategy for data partitioning. The estimated pooled proportion of teeth surviving over 4–5 years following treatment was 93% (95% CI: 92%, 94%), whilst the proportion of teeth surviving over 8–10 years [87% (95% CI 82%, 92%)] was 6% lower, suggesting that tooth loss continued many years after treatment, warranting a much longer duration of follow-up in future studies. The above-mentioned figures on tooth survival after root canal treatment were slightly lower than the previous estimated pooled weighted 2–4 year survival rates for implant-supported

single crowns [96% (95% CI: 94%, 97%)]; but much higher than the respective figures for tooth extraction with fixed-prosthesis placement (78–79%) (Torabinejad *et al.* 2007). These results are supportive of the notion that both options; root canal treatment and tooth replacement with an implant-supported single crown could be considered as viable options during treatment planning for teeth with endodontic problems. However, both the present and the previous data (Torabinejad *et al.* 2007) were limited by the small number of studies included; therefore, the results should be interpreted with caution.

Amongst the many reasons cited for extraction of root-treated teeth, the most common reported by a study published beyond the time frame of this review, were 'large carious lesion' or 'unrestorable tooth', followed by 'tooth fracture', 'periodontal disease' and last of all 'endodontically related diseases' (Chen *et al.* 2008). The findings support those of the present review, which revealed a high probability of tooth survival (86–93%) following root canal treatment; if taken as a measure of success, the values exceed those for the probabilities of success judged by periapical healing (74–85%) (Ng *et al.* 2007, 2008b). The prognostic factors for tooth survival and periapical healing following root canal treatment have not been previously investigated using the same patient and tooth dataset; therefore, the presence or absence of commonality between prognostic factors for the two outcome measures would be mere speculation at present. It is likely that unless the cause of tooth extraction was failure of periapical healing (Ng *et al.* 2008a,b), the prognostic factors would be different for the two outcome measures.

Previous evidence for prognostic factors predicting tooth survival was weak. Although 19 potential factors have been investigated in the studies reviewed, most were only analysed individually by a single study; therefore, estimations of combined effect were only possible for eight factors. For some of these eight factors, meta-analyses were carried out on data pooled from only 2–3 studies; therefore, the results of these analyses should be interpreted with caution.

Investigation of the prognostic factors for tooth survival has in previous studies involved either the chi-square test to compare odds (Alley *et al.* 2004, Lynch *et al.* 2004, Salehrabi & Rotstein 2004, Chen *et al.* 2008) or the log-rank test to compare survival functions (Mantel–Haenszel method) (Stoll *et al.* 2005, Lumley *et al.* 2008, Tickle *et al.* 2008). Only Caplan and colleagues (*Caplan & Weintraub 1997,

Aquilino & Caplan 2002, Caplan *et al.* 2002, 2005) used multiple logistic or Cox regression models to account for the potential confounders for the factor of interest when comparing odds or hazards, respectively. Chi-square tests compare the proportion of events by the groups of subjects under investigation taking into account only those subjects who can be observed and without accounting for the effects of potential confounders, giving potentially biased estimates. Investigation of tooth survival is more appropriately conducted using life table or Kaplan–Meier curves to estimate the cumulative probability of survival in each group at different times after the starting point. The survival experiences of the group can then be compared using a log-rank test, also called the Mantel–Haenszel test. The major drawbacks of the log-rank test are as follows: first, it does not give the size of the effect related to a particular factor of interest; and secondly, that it does not account for any other factor that may affect survival time. This drawback may be overcome by stratifying the data and using stratified log-rank tests. In more complicated cases, it is more appropriate to use a form of multiple regression (e.g. Cox regression) where the survival is modelled through the hazard function or event rate.

For the present meta-analysis, the data on observed proportion of teeth surviving were extracted for estimating the overall effect of influencing factors expressed in odds ratio as data on hazards were not available from most studies. Nevertheless, meta-analyses of pooled data revealed that only four conditions (non-molar teeth, teeth with two proximal contacts, teeth restored with a crown, teeth not functioning as fixed-prosthesis abutment) were significantly associated with better survival. Only 2–3 studies contributed data for 'number of proximal contacts' and 'functioning as abutment'; therefore, the results should be interpreted with caution. Generally, substantial heterogeneity was found amongst studies when the overall effects of a number influencing factors were estimated using meta-analysis. Although the intention was to carry out meta-regression analysis to investigate the type of study (prospective versus retrospective) and the duration of follow-up as the sources of heterogeneity, this was not possible because of insufficient information as well as the small number of studies available.

Different tooth morpho-types may vary in susceptibility to tooth fracture (Cavel *et al.* 1985), a common reason for tooth loss after treatment; either because of inherent weakness in formation (Khera *et al.* 1990) or

because of different occlusal loading patterns (Cavel *et al.* 1985). Previous reports have implicated maxillary premolars and mandibular molars as having a greater susceptibility to fracture (Eakle *et al.* 1986, Lagouvardos *et al.* 1989). The present review would appear to support these notions given the finding that 'non-molar' teeth survived significantly better than other teeth after root canal treatment, whilst anterior teeth survived better than premolar teeth.

The unfavourable distribution of occlusal force and higher non-axial stress on posterior teeth with <2 proximal contacts may render such teeth more susceptible to fracture (and therefore extraction) following root canal treatment. Teeth protected with a crown after root canal treatment may experience more favourable load distribution and therefore be less susceptible to fracture. The direct and injudicious clinical inference from this statement is that cast restorations should preferably be placed on all teeth after root canal treatment, but this may be a gross exaggeration of the true need as there is a lack of evidence on the inter-relationship between tooth morpho-type, the extent and distribution of coronal tooth tissue loss, the type of final restoration and the pattern of occlusal loading. In agreement with the above-mentioned speculation, the probability of clinical success of premolars and molars was found to be significantly improved with coronal coverage restorations but not that of anterior teeth when the failure event was defined as dislodgment, fracture of tooth or root structure, vertical root fracture or iatrogenic root perforation (Sorensen & Martinoff 1984).

Assessment of the restorability of teeth prior to endodontic treatment and tooth restoration must remain a prerequisite but the process by which dentists perform such an assessment is subject to considerable variation (Brennan 2009). Although a restorability index is available to guide clinicians in assessing the remaining tooth structure (McDonald & Setchell 2005), its validation by long-term tooth survival data has not yet been achieved. Two previous studies not included in the present review (Reeh *et al.* 1989, Nagasiri & Chitmongkolsuk 2005) found posterior teeth with compromised marginal ridges (mesially and/or distally) were associated with poorer survival of the restoration and tooth. The inclusion of assessment of survival of the restoration together with tooth survival complicated the clinical inferences drawn from their data. There is a need to carry out long-term prospective studies to investigate the influence of restorative factors individually and interactively on tooth survival following root canal treatment. The restorative factors should ideally include the amount and distribution of remaining tooth structure, the amount and distribution of occlusal loading on the tooth under function, and the type of final restoration. When investigating the influence of restorative factors, it is also important to consider the skills (qualification) of the operator providing the restoration, in particular for cast restorations as dentist's experience and qualifications are significant prognostic factors for restoration survival (Lucarotti *et al.* 2005, Burke & Lucarotti 2008).

Longer follow-up studies with larger sample sizes are also warranted for teeth exhibiting cracks prior to root canal treatment as they pose a dilemma in decision-making on treatment options. Although Tan *et al.* (2006) performed detailed analyses on the influence of various parameters of pre-existing cracks on survival of root-treated teeth, their results were compromised by the small sample size ($n = 50$ teeth) and short duration of follow-up (2 years). The lack of statistical power in their study is reflected in the large but statistically insignificant effect of extension of cracks (OR = 2.5; 95% CI 0.6, 8.2) on tooth survival.

Amongst the intra-operative factors, the effect of large canal preparation dimensions, chemically active irrigants and medicaments, such as sodium hypochlorite and calcium hydroxide on tooth survival should also be investigated in future prospective long-term tooth survival studies. Currently available *in vitro* data reveal that irrigation with sodium hypochlorite used alone at high concentration (5%) or alternately with ethylene-diamine-tetra-acetic acid (EDTA) (Sim *et al.* 2001, Rajasingham *et al.* 2010, Sobhani *et al.* 2010) as well as dressing the canal with calcium hydroxide (Grigoratos *et al.* 2001, Andreasen *et al.* 2002) may have a weakening effect on dentine; therefore, they may potentially increase the risk of tooth fracture and tooth loss. The clinical dilemma is, therefore, one of where to place the emphasis in the contradictory requirements for periapical healing and long-term tooth survival; conservative techniques may enhance tooth survival but compromise periapical healing, whilst aggressive techniques may reduce tooth survival but enhance periapical healing.

Apart from tooth fracture, periodontal disease was another common reason for tooth extraction following root canal treatment (Chen *et al.* 2008). However, the effect of preoperative periodontal status of the teeth has never been investigated and warrants attention in future studies.

Conclusion

The results of this review should be interpreted with caution and cannot be considered to give definitive answers because of the limitation of the data as well as its retrospective and heterogeneous nature. The pooled probabilities of tooth survival 2–10 years following root canal treatment ranged from 86% to 93%. There were substantial differences in study characteristics to hinder effective direct comparison of findings. The evidence on the prognostic factors for tooth survival was very weak. From the data available for meta-analyses, four conditions were identified to significantly improve tooth survival. They are listed in descending order of influence (i) teeth restored with a crown after treatment; (ii) teeth with mesial and distal proximal contacts; (iii) teeth not functioning as abutment for removable or fixed prosthesis; and (iv) non-molar teeth. In essence, the available evidence supports the current intuitive premise that healthful tooth survival is likely to be influenced by the distribution, amount, strength and integrity of remaining tooth tissue, the occlusal and functional loading on the tooth and the manner in which that load is distributed within the remaining tooth tissue (Gulabivala 2004). This review has also highlighted the need for long-term prospective studies with comprehensive data to investigate the prognostic factors for root canal treatment outcome using both tooth survival as well as periapical healing as outcome measures on the same sample material.

References

Adolphi G, Zehnder M, Bachmann LM, Göhring TN (2007) Direct resin composite restorations in vital versus root-filled posterior teeth: a controlled comparative long-term follow-up. *Operative Dentistry* **32**, 437–42.

Alley BS, Kitchens GG, Alley LW, Eleazer PD (2004) A comparison of survival of teeth following endodontic treatment performed by general dentists or by specialists. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **98**, 115–8.

Andreasen JO, Farik B, Munksgaard EC (2002) Long-term calcium hydroxide as a root canal dressing may increase risk of root fracture. *Dental Traumatology* **18**, 134–7.

Aquilino SA, Caplan DJ (2002) Relationship between crown placement and the survival of endodontically treated teeth. *Journal of Prosthetic Dentistry* **87**, 256–63.

Basmadjian-Charles CL, Farge P, Bourgeois DM, Lebrun T (2002) Factors influencing the long-term results of endodontic treatment: a review of the literature. *International Dental Journal* **52**, 81–6.

Brennan P (2008) *A survey of different groups of dentists to investigate their approach to assessment of tooth restorability prior to root canal treatment.* MsC thesis. London, UK: University College London.

Burke FJ, Lucarotti PS (2008) Ten-year outcome of crowns placed within the General Dental Services in England and Wales. *Journal of Dentistry* **37**, 31–8.

Caplan DJ, Weintraub JA (1997) Factors related to loss of root canal filled teeth. *Journal of Public Health Dentistry* **57**, 31–9.

Caplan DJ, Kolker J, Rivera EM, Walton RE (2002) Relationship between number of proximal contacts and survival of root canal treated teeth. *International Endodontic Journal* **35**, 193–9.

Caplan DJ, Cai J, Yin G, White BA (2005) Root canal filled versus non-root canal filled teeth: a retrospective comparison of survival times. *Journal of Public Health Dentistry* **65**, 90–6.

Card SJ, Sigurdsson A, Ørstavik D, Trope M (2002) The effectiveness of increased apical enlargement in reducing intracanal bacteria. *Journal of Endodontics* **28**, 779–83.

Cavel WT, Kelsey PK, Blankenau RJ (1985) An in vivo study of cuspal fracture. *The Journal of Prosthetic Dentistry* **53**, 38–42.

Chen SC, Chueh LH, Hsiao CK, Tsai MY, Ho SC, Chiang CP (2007) An epidemiologic study of tooth retention after nonsurgical endodontic treatment in a large population in Taiwan. *Journal of Endodontics* **33**, 226–9.

Chen S-C, Chueh L-H, Hsiao CK, Wu H-P, Chiang C-P (2008) First untoward events and reasons for tooth extraction after nonsurgical endodontic treatment in Taiwan. *Journal of Endodontics* **34**, 671–4.

Cochran WG (1954) The combination of estimates from different experiments. *Biometrics* **10**, 101–29.

Creugers NHJ, Kreulen CM, Snoek PA, de Kanter RJAM (2000) A systematic review of single-tooth restorations supported by implants. *Journal of Dentistry* **28**, 209–17.

Dammaschke T, Steven D, Kaup M, Ott KH (2003) Long-term survival of root-canal-treated teeth: a retrospective study over 10 years. *Journal of Endodontics* **29**, 638–43.

De Backer H, Van Maele G, De Moor N, Van den Berghe L (2006) Single-tooth replacement: is a 3-unit fixed partial denture still an option? A 20-year retrospective study *The International Journal of Prosthodontics* **19**, 567–73.

De Backer H, Van Maele G, Decock V, Van den Berghe L (2007) Long-term survival of complete crowns, fixed dental prostheses, and cantilever fixed dental prostheses with posts and cores on root canal-treated teeth. *The International Journal of Prosthodontics* **20**, 229–34.

Del Fabbro M, Taschieri S, Testori T, Francetti L, Weinstein RL (2007) Surgical versus non-surgical endodontic re-treatment for periradicular lesions (Review). *The Cochrane Collaboration* **3**, 1–14.

Eakle ES, Maxwell EH, Braly BV (1986) Fracture of posterior teeth in adults. *Journal of the American Dental Association* **112**, 215–8.

Ferrari M, Cagidiaco MC, Grandini S, De Sanctis M, Goracci C (2007) Post placement affects survival of endodontically treated premolars. *Journal of Dental Research* **86**, 729–34.

Figini L, Lodi G, Gorni F, Gagliani M (2007) Single versus multiple visits for endodontic treatment of permanent teeth. *Cochrane Database of Systematic Reviews* **17**, CD005296.

Friedman S, Mor C (2004) The success of endodontic therapy – healing and functionality. *Journal – California Dental Association* **32**, 496–503.

Glazer B (2000) Restoration of endodontically treated teeth with carbon fibre posts – a prospective study. *Journal of Canadian Dental Association* **66**, 613–8.

Grigoratos D, Knowles J, Ng Y-L, Gulabivala K (2001) Effect of sodium hypochlorite and calcium hydroxide on the modulus of elasticity and flexural strength of dentine. *International Endodontic Journal* **34**, 113–9.

Gulabivala K (2004) Restoration of the root-treated tooth. In: Stock C, walker R, Gulabivala K, ed. *Endodontics*, 3rd edn. Oxford, UK: Elsevier Mosby, pp. 279–306.

Gulabivala K, Patel B, Evans G, Ng Y-L (2005) Effects of mechanical and chemical procedures on root canal surfaces. *Endodontic Topics* **10**, 103–22.

Hand RE, Smith ML, Harrison JW (1978) Analysis of the effect of dilution on the necrotic tissue dissolution property of sodium hypochlorite. *Journal of Endodontics* **4**, 60–4.

Hansen EK, Asmussen E, Christiansen NC (1990) In vivo fractures of endodontically treated posterior teeth restored with amalgam. *Endodontics and Dental Traumatology* **6**, 49–55.

Hepworth MJ, Friedman S (1997) Treatment outcome of surgical and non-surgical management of endodontic failures. *Journal of Canadian Dental Association* **63**, 364–71.

Huang T-Y, Gulabivala K, Ng Y-L (2008) A bio-molecular film *ex vivo* model to evaluate the influence of canal dimensions and irrigation variables on the efficacy of irrigation. *International Endodontic Journal* **41**, 60–71.

Khera SC, Carpenter CW, Vetter JD, Staley RN (1990) Anatomy of cusps of posterior teeth and their fracture potential. *Journal of Prosthetic Dentistry* **64**, 139–47.

Kojima K, Inamoto K, Nagamatsu K *et al.* (2004) Success rate of endodontic treatment of teeth with vital and nonvital pulps. A meta-analysis. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **97**, 95–9.

Kolker JL, Damiano PC, Flach SD *et al.* (2006) The cost-effectiveness of large amalgam and crown restorations over a 10-year period. *Journal of Public Health Dentistry* **66**, 57–63.

Lagouvardos P, Sourai P, Douvitsas G (1989) Coronal fracture of posterior teeth. *Operative Dentistry* **14**, 28–32.

Lazarski MP, Walker WA III, Flores CM, Schindler WG, Hargreaves KM (2001) Epidemiological evaluation of the outcomes of non-surgical root canal treatment in a large cohort of insured dental patients. *Journal of Endodontics* **27**, 791–6.

Lee S-J, Wu M-K, Wesselink PR (2004) The efficacy of ultrasonic irrigation to remove artificially placed dentine debris from different-sized simulated plastic root canals. *International Endodontic Journal* **37**, 607–12.

Lewsey JD, Gilthorpe MS, Gulabivala K (2001) An introduction to meta-analysis within the framework of multilevel modelling using the probability of success of root canal treatment as an illustration. *Community Dental Health* **18**, 131–7.

Lucarotti PS, Holder RL, Burke FJ (2005) Outcome of direct restorations placed within the general dental services in England and Wales (Part 3): variation by dentist factors. *Journal of Dentistry* **33**, 827–35.

Lumley PJ, Lucarotti PS, Burke FJ (2008) Ten-year outcome of root fillings in the General Dental Services in England and Wales. *International Endodontic Journal* **41**, 577–85.

Lynch CD, Burke FM, NíRiordáin R, Hannigan A (2004) The influence of coronal restoration type on the survival of endodontically treated teeth. *European Journal of Prosthodontics and Restorative Dentistry* **12**, 171–6.

Mackie IC, Worthington HV, Hill FJ (1993) A follow-up study of incisor teeth which had been treated by apical closure and root filling. *British Dental Journal* **175**, 99–101.

Mannocci F, Bertelli E, Sherriff M, Watson TF, Ford TR (2002) Three-year clinical comparison of survival of endodontically treated teeth restored with either full cast coverage or with direct composite restoration. *Journal of Prosthetic Dentistry* **88**, 297–301.

Mannocci F, Qualtrough AJ, Worthington HV, Watson TF, Pitt Ford TR (2005) Randomized clinical comparison of endodontically treated teeth restored with amalgam or with fiber posts and resin composite: five-year results. *Operative Dentistry* **30**, 9–15.

McDonald A, Setchell DJ (2005) Developing a tooth restorability index. *Dental Update* **32**, 343–8.

Mindiola MJ, Mickel AK, Sami C, Jones JJ, Lalumandier JA, Nelson SS (2006) Endodontic treatment in an American Indian population: a 10-year retrospective study. *Journal of Endodontics* **32**, 828–32.

Miyamoto T, Morgano SM, Kumagai T, Jones JA, Nunn ME (2007) Treatment history of teeth in relation to the longevity of the teeth and their restorations: outcomes of teeth treated and maintained for 15 years. *Journal of Prosthetic Dentistry* **97**, 150–6.

Molven O (1976) Tooth mortality and endodontic status of a selected population group. Observations before and after treatment. *Acta Odontologica Scandinavica* **34**, 107–16.

Naert I, Koutsikakis G, Quirynen M, Duyck J, van Steenberghe D, Jacobs R (2002) Biologic outcome of implant-supported restorations in the treatment of partial edentulism. Part 2: a longitudinal radiographic study. *Clinical Oral Implants Research* **13**, 390–5.

Nagasiri R, Chitmongkolsuk S (2005) Long-term survival of endodontically treated molars without crown coverage: a retrospective cohort study. *Journal of Prosthetic Dentistry* **93**, 164–70.

Nair PN, Henry S, Cano V, Vera J (2005) Microbial status of apical root canal system of human mandibular first molars with primary apical periodontitis after 'one visit' endodontic treatment. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics*, **99**, 231–52.

Ng Y-L, Mann V, Rahbaran S, Lewswy J, Gulabivala K (2007) Outcome of primary root canal treatment: systematic review of the literature – Part 1. Effects of study characteristics on probability of success. *International Endodontic Journal* **40**, 12–39.

Ng Y-L, Mann V, Rahbaran S, Lewsey J, Gulabivala K (2008a) Outcome of primary root canal treatment: systematic review of the literature – Part 2. Influence of clinical factors. *International Endodontic Journal* **41**, 6–31.

Ng Y-L, Mann V, Rahbaran S, Lewsey J, Gulabivala K (2008b) Outcome of secondary root canal treatment: a systematic review of the literature. *International Endodontic Journal* **41**, 1026–46.

Paik S, Sechrist C, Torabinejad M (2004) Levels of evidence for the outcome of endodontic retreatment. *Journal of Endodontics* **30**, 745–50.

Parris J, Wilcox L, Walton R (1994) Effectiveness of apical clearing: histological and radiographical evaluation. *Journal of Endodontics* **20**, 219–24.

Peng L, Ye L, Tan H, Zhou X (2007) Outcome of root canal obturation by warm gutta-percha versus cold lateral condensation: a meta-analysis. *Journal of Endodontics* **33**, 106–9.

Piovesan EM, Demarco FF, Cenci MS, Pereira-Cenci T (2007) Survival rates of endodontically treated teeth restored with fiber-reinforced custom posts and cores: a 97-month study. *The International Journal of Prosthodontics* **20**, 633–9.

Rajasingham R, Knowles JC, Ng Y-L, Gulabivala K (2010) The effect of sodium hypochlorite and ethylenediaminetetraacetic acid irrigation, individually and in alternation, on tooth surface strain. *International Endodontic Journal* **43**, 31–40.

Reeh ES, Messer HH, Douglas WH (1989) Reduction in tooth stiffness as a result of endodontic and restorative procedures. *Journal of Endodontics* **15**, 512–6.

Rollison S, Barnett F, Stevens RH (2002) Efficacy of bacterial removal from instrumented root canals in vitro related to instrumentation technique and size. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **94**, 366–71.

Sackett DL, Rosenberg WM, Gray JA, Haynes RB, Richardson WS (1996) Evidence based medicine: what it is and what it isn't. *British Medical Journal* **13**, 71–2.

Salehrabi R, Rotstein I (2004) Endodontic treatment outcomes in a large patient population in the USA: an epidemiological study. *Journal of Endodontics* **30**, 846–50.

Salvi GE, Siegrist Guldener BE, Amstad T, Joss A, Lang NP (2007) Clinical evaluation of root filled teeth restored with or without post-and-core systems in a specialist practice setting. *International Endodontic Journal* **40**, 209–15.

Sathorn C, Lalamara JE, Palamara DM, Messer HH (2005a) Effect of root canal size and external root surface morphology on fracture susceptibility and pattern: a finite element analysis. *Journal of Endodontics* **31**, 288–92.

Sathorn C, Parashos P, Messer HH (2005b) Effectiveness of single- versus multiple-visit endodontic treatment of teeth with apical periodontitis: a systematic review and meta-analysis. *International Endodontic Journal* **38**, 347–55.

Schaeffer MA, White RR, Walton RE (2005) Determining the optimal obturation length: a meta-analysis of literature. *Journal of Endodontics* **31**, 271–4.

Sim TP, Knowles JC, Ng YL, Shelton J, Gulabivala K (2001) Effect of sodium hypochlorite on mechanical properties of dentine and tooth surface strain. *International Endodontic Journal* **34**, 120–32.

Sobhani OE, Gulabivala K, Knowles JC, Ng Y-L (2010) The effect of irrigation time, root morphology and dentine thickness on tooth surface strain when using 5% NaOCl and 17% EDTA. *International Endodontic Journal* **43**, 190–9.

Sorensen JA, Martinoff JY (1984) Intraconronal reinforcement and coronal coverage: a study of endodontically treated teeth. *The Journal of Prosthetic Dentistry* **51**, 780–4.

Stavropoulou AF, Koidis PT (2007) A systematic review of single crowns on endodontically treated teeth. *Journal of Dentistry* **35**, 761–7.

Stoll R, Betke K, Stachniss V (2005) The influence of different factors on the survival of root canal fillings: a 10-year retrospective study. *Journal of Endodontics* **31**, 783–90.

Tan L, Chen NN, Poon CY, Wong HB (2006) Survival of root filled cracked teeth in a tertiary institution. *International Endodontic Journal* **39**, 886–9.

Tickle M, Milsom K, Qualtrough A, Blinkhorn F, Aggarwal VR (2008) The failure rate of NHS funded molar endodontic treatment delivered in general dental practice. *British Dental Journal* **204**, 1–6, discussion 254–5.

Tilashalski KR, Gilbert GH, Boykin MJ, Shelton BJ (2004) Root canal treatment in a population-based adult sample: status of teeth after endodontic treatment. *Journal of Endodontics* **30**, 577–81.

Torabinejad M, Kutsenko D, Machnick TK, Ismail A, Newton CW (2005) Levels of evidence for the outcome of nonsurgical endodontic treatment. *Journal of Endodontics* **31**, 637–46.

Torabinejad M, Anderson P, Bader J *et al.* (2007) Outcomes of root canal treatment and restoration, implant-supported single crowns, fixed partial dentures, and extraction without replacement: a systematic review. *Journal of Prosthetic Dentistry* **98**, 285–311.

Wegner PK, Freitag S, Kern M (2006) Survival rate of endodontically treated teeth with posts after prosthetic restoration. *Journal of Endodontics* **32**, 928–31.

White SN, Akhparyan E, Kutshenko D, Torabinejad M (2007) Endodontics and tooth retention. *International Journal of Prosthodontics* **20**, 343–4.

Willershausen B, Tekyatan H, Krummenauer F, Briseño Marroquin B (2005) Survival rate of endodontically treated teeth in relation to conservative vs post insertion techniques – a retrospective study. *European Journal of Medical Research* **10**, 204–8.

Zitzmann NU, Krastl G, Hecker H, Walter C, Weiger R (2009) Endodontics or implants? A review of decisive criteria and guidelines for single tooth restorations and full arch reconstructions *International Endodontic Journal* **42**, 757–74.