Received: 29 March 2022 | Accepted: 25 April 2022

DOI: 10.1111/iej.13757

INTERNATIONAL ENDODONTIC JOURNAL | WILEY

REVIEW ARTICLE

Health economic evaluation of endodontic therapies

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Abstract

Healthcare is an expensive endeavour, and it is likely that costs for endodontic treatment will grow over the next decade. The assessment of costs and, in most cases, health outcomes, and the comparison of the cost-health ratio of interventions, is at the heart of health economics. The present review aims to introduce the main concepts of health economic analysis, to systematically review the existing economic endodontic literature, and to deduce further action for the community. Overall, the identified body of evidence on the health economics of endodontic therapies is heterogenous and has several limitations: Not all studies identified robust data to inform their analyses and many relied on a wide range of assumptions, which were only explored for their impact in a limited way. However, a number of themes were identified from the review: (1) Maintaining pulpal vitality is preferable over root canal treatment if possible when it comes to cost-effectiveness. (2) Retaining teeth is usually more cost-effective than removing and replacing them. (3) Endodontic retreatment may be clinically indicated, but not always cost-effective, and should hence be considered carefully. In conclusion, the general sparsity of economic analyses is a concern, as decision makers such as commissioners or those funding dental care increasingly rely on them. The endodontic community is called to action to improve the competency of both researchers to conduct such analyses and consider them when planning research, but also clinicians who should factor in health economics when assigning interventions. Health economics should become an accepted pillar of endodontic research.

KEYWORDS

cost-effectiveness, economics, endodontics, Markov model, restoration

THE RELEVANCE OF COSTS AND COST-EFFECTIVENESS IN ENDODONTICS

Healthcare is an expensive endeavour, and each year costs for health are increasing overproportionally compared with the GDP of most countries. By 2050, the costs for healthcare are expected to grow to 15 trillion US Dollars (USD; Chang et al. 2019). Dental care is one of the larger elements contributing to these healthcare costs; indeed, the management of dental diseases has been estimated to generate costs of 357 billion USD per year worldwide (Righolt et al. 2018).

The treatment of endodontic conditions includes vital pulp therapy (direct capping, pulpotomy), root canal treatment and retreatment, surgical endodontic treatment (apicectomy), and the management of dental trauma involving the pulp. Worldwide, more than 15 million people are estimated to receive endodontic care each year, and per day 41 000 teeth are managed endodontically (Jones 2016); endodontics is one of the fastest growing specialties in dentistry, reflecting the overall trend towards retaining instead of replacing teeth if clinically, technically, and economically feasible.

Assessing the outcomes of endodontic therapy is complex: For example, most endodontic treatments are measurable and measured using short-term outcomes (such as pain in the first days or weeks after the therapy) or mid-term outcomes (such as healing of an apical lesion); long-term outcomes and the lifelong sequelae (such as the need and type of any endodontic or restorative retreatment, the option to retain, or the need to remove the tooth) are usually not reflected but relevant given that they have tangible impact on patients but also healthcare systems.

One outcome which is relevant regardless of whether assessed short term, mid term, or long term is costs: Payers – patients, insurers, or other third parties – will be interested in these costs as a major factor in their decision making; costs can be used to weigh treatment alternatives of similar clinical or patient-reported outcomes, but also those with different outcomes. Generally, there is increasing interest in the health economic characteristics of dental treatments, as reflected by a growing number of studies in the field (for the year 1990, there were 309 entries in PubMed for "dentistry AND economic", whilst for 2020 this number was 937).

Demonstrating that endodontic interventions are economically feasible and possibly preferable over other interventions such as tooth replacement, but also evaluating the comparative economics of different endodontic treatments, is relevant for endodontic specialists, general practitioners, patients, and healthcare policymakers. This review will describe aspects to consider in heath economic analyses and what types of analyses can be chosen, and eventually appraise and synthesize the available literature on health economic analysis in endodontics.

HEALTH ECONOMIC ANALYSES

There are a range of aspects to consider when performing health economic analyses, namely the cost perspective, the health outcome, the horizon of the analysis, amongst others.

Cost perspective

Costs can be assessed from a provider's perspective, reflecting direct costs, including medical costs, but also non-medical ones such as those for transporting patients. In this case, the costs for staff involved in a therapy (e.g., measuring the time a dentist and a dental nurse require to perform a root canal treatment, multiplied by their gross salary), plus the materials involved as well as costs for running the surgery (heating, electricity, depreciation, etc.) are reflected.

Alternative approaches build on the assessment of costs occurring to payers, and often involve usage of fee items which providers use to claim reimbursement from patients or payers (payer perspective). These fee items will not perfectly match the costs of each individual cases from a provider perspective but are oftentimes set or negotiated to reflect the true costs occurring to providers (plus overhead) to some degree.

Besides direct costs, indirect costs are often relevant; they reflect expenses incurred from being less productive at work or school (presenteeism) or even being absent (absenteeism) due to morbidity or mortality, but also due to time spent for treatment or travelling to receive care. Indirect costs of oral conditions have been found to be substantial (Righolt et al. 2018) but require knowledge on a number of factors, such as the impact of an oral condition on presenteeism or absenteeism, but also their duration. Moreover, quantification of indirect costs needs to reflect on the value assigned to the human productive capital lost, for example, the monetary value of a worker in a factory falling ill due to a dental condition. Assessing both the direct and the indirect costs will account for the costs occurring to society (societal costs).

Health outcomes

Health economic analysis reflects on the costs, as laid out, and (for many analyses) the health outcomes generated by an intervention. Health outcomes are used to characterize the four main types of comparative health economic analyses (comparing two or more interventions) (Vernazza et al., 2012):

- *Cost-of-disease analyses*. These do not reflect on the health outcome, but only costs, the assumption behind these analyses being that health outcomes between the assessed interventions are identical. This assumption is nearly never met, which is why these analyses are uncommon.
- *Cost-effectiveness analyses*. These types of analyses reflect on a clinically measurable outcome, termed effectiveness, and weigh this effectiveness against the costs. Effectiveness could stem from real-life data (e.g., claims data) or prospectively collected data (e.g., randomized trials); note that for the latter, the term efficacy is usually used in the clinical trials domain, whilst health

economists nevertheless use the term effectiveness. Effectiveness can be the time a tooth is retained, measured in years; healing of an apical lesions after root canal treatment or successful vital pulp therapy, both measured in % of the treated teeth; or the pain patients experience after endodontic therapy, measured on a visual analogue scale, etc. Effectiveness measurement needs to be performed identically in both groups to allow cost-effectiveness analyses. In this case, the difference in costs and the difference in effectiveness can be determined and expressed as an incremental cost-effectiveness ratio. These ratios can be positive (reflecting that one comparator is more costly, but also more effective than the other one: additional money "buys" effectiveness) or negative (one comparator being more costly, but less effective). In the first case, a decision problem occurs (which therapy to choose: the more effective or the less costly one?); cost-effectiveness is then decided differently for payers with different willingness-to-pay. In the second case, no decision problem is present; one therapy is clearly more cost-effective than the other.

- *Cost-utility analyses*. Utility of an intervention is usually measured as quality- or disability-adjusted life years (QALYs, DALYs). To express QALYs or DALYs, subjective values need to be placed onto a certain health state, and then the duration of any health reduction is multiplied with that value. If the valuations and time estimates are fully accurate, this allows different diseases (e.g., pulpitis and periodontitis, but also pulpitis and back pain) to be expressed on the same scale. Determining utility values in dentistry has not been validated extensively, and it remains unclear what value patients place on certain dental health states (e.g., a sound versus a root canal filled tooth; Balevi & Shepperd 2007). Similarly, measuring the time of a certain health state (e.g., pain due to pulpitis) is not always possible in a reliable way.
- *Cost-benefit analyses*. Here, the health outcomes (effectiveness, utility) are transformed into a monetary value, that is, costs and health are now expressed on the same scale and can be weighed against each other transparently. However, transforming disease into monetary value comes with the need for subjective determination of the value of health (similar to utility, but now with the difference that the valuation is monetary) and has very rarely been performed (Balevi & Shepperd 2007).

Data generation and analysis

The data to inform health economic analyses, that is, cost and health outcome data, can be generated via two strategies:The first builds on data from one rather comprehensive source, for example, a clinical pro- or retrospective cohort study or an interventional study or large claims databases. If planned prospectively, costs for labour and material, but also transport (e.g., visiting their endodontist) or indirect costs (for patients being off from work for their root canal treatment appointments), can be recorded in detail (also termed micro-costing). If conducted retrospectively (e.g., based on electronic health records or claims data), costs can also be estimated using fee items, which are usually recorded and reflect – as outlined – the payer's perspective. Such studies come with high internal validity if conducted appropriately, that is, they can inform interested parties towards the likely true cost-effectiveness, cost-utility, or cost-benefit within this study setting. This, on the other hand, means their generalizability to other settings (non-study settings, practices, populations) may be limited, that is, their external validity may be compromised to some degree. Their most important limitation, however, is the follow-up such studies can provide: Randomized trials in endodontics follow-up individuals for months or few years; cohort studies building on routine (e.g., health record) data may manage follow-up for 5–10 years, but only seldomly longer. The sequelae of endodontic therapy, however, are relevant far longer, as laid out: After vital pulp therapy, for example, the need for root canal treatment may occur over the next decade; the failure of this root canal treatment may then occur another decade later, followed by either surgical or non-surgical retreatment, extraction or replacement of the tooth, etc. All of these sequelae can only be accounted for in such studies in a limited way, but have been found relevant if one is interested in comprehensively assessing the cost-effectiveness (Schwendicke, 2019).

The second strategy builds on a range of data sources and combines them using mathematical models. Modelling allows the natural path of endodontically treated teeth or patients to be simulated over the long term, for example, throughout their lifetime. Teeth or patients are initially placed in a certain health state (e.g., direct capping performed; root canal treatment performed) and can move from one to another health status (e.g., pulp necrosis requiring root canal treatment; non-surgical retreatment needed). The probability of every move ("translation") is based on data obtained from a range of sources, such as cohort studies (for example those reporting on the success of direct pulp capping) or meta-analyses (for example on the survival of root canal-treated teeth). By combining multiple translations, long-term sequences of events can be reflected, which accounts for the described fact that most endodontic therapies have long-term impacts which a single study cannot fully consider. For each translation, treatments and costs are assumed. These costs are estimated based on various data sources, such as previous clinical studies (which might have used micro-costing) or fee item catalogues. The advantages of combining multiple data sources and leveraging data by modelling are (1) the option for long-term analyses, (2) lower costs given that researchers make use of existing data instead of collecting new data, (3) the possibility to compare not only two, but also three, four, or ten different interventions for their cost-effectiveness (if sufficient data on health and costs are available), and (4) the fact that they can be used to analyse health economics in different healthcare systems or over different time horizons using a comparable framework. Moreover, such studies allow multiple input parameters to be varied (e.g., costs, effectiveness of certain endodontic therapies) and thereby explore their importance, but also the relevance of their uncertainty on cost-effectiveness. Their main weakness is that these studies rely on a range of assumptions, for example, those lying within the structure of their model (structural uncertainty), their input data (parameter uncertainty), the population modelled (heterogeneity), etc., which need to be explored in detail to reduce the risk of erroneous conclusions from modelling. These explorations can be done in univariate sensitivity analyses, varying one parameter at a time, or by joint probability sensitivity analyses. The latter allows the uncertainty of various parameters combined by sampling each parameter from its uncertainty distribution to be reflected upon (e.g., a normal distribution around the mean, etc., for a certain risk, such as needing root canal treatment after direct pulp capping) repeatedly. By doing so, in each of these repeated simulations, each parameter is varied, and that combined variation then allows to estimate the resulting joint uncertainty in effectiveness and costs.

Uncertainty analyses allow the impact of uncertainty on cost-effectiveness to be gauged. If, for example, specific parameters are uncertain but their univariate and combined variation does not lead to any relevant change in cost-effectiveness rankings, it is acceptable. If, however, uncertainty of a specific parameter means that under one assumption (e.g. low risk of root canal treatment failing over 10 years) leads to cost-effectiveness of one comparator (e.g., root canal treatment) over another (e.g., removal and implant-based replacement of the tooth), whilst another assumption (high risk of root canal treatment failure) reverses this ranking (now, implant-based replacement is more cost-effective), this should be highlighted: Decision makers should consider this uncertainty in any decision or postpone the decision until more certainty has emerged.

Value of health and value of information

One last important parameter which is usually uncertain in health economic analyses is the value decision makers places on health (the problem of decision making was touched upon briefly above). Whilst in some healthcare systems and for some health outcomes (such as QUALYs), threshold values have been defined (Bertram et al. 2016), such acceptability thresholds are largely absent for dentistry or, specifically, endodontics. This also relates to the discussed difficulties in assigning values to certain oral health states. Nevertheless, exploring the acceptability of an endodontic intervention depending on a payer's willingness-to-pay for a certain health state (e.g., retaining a tooth by a root canal treatment instead of losing it)

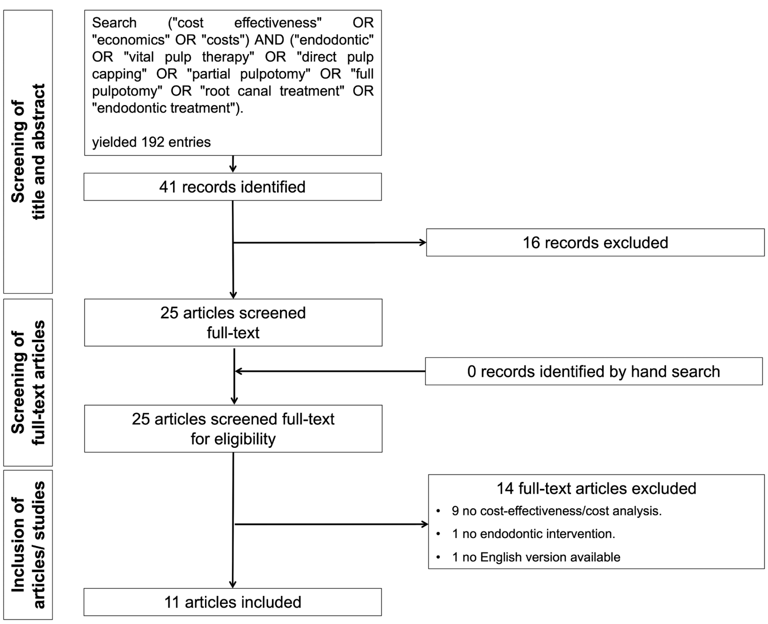

FIGURE 1 Flowchart of the literature selection. Two databases were screened for studies performing endodontic health economic analyses.

can be performed. These analyses are offering additional insights not only in the trade-off between health and costs (with increasing willingness-to-pay, health benefits of one intervention over the other become more important than cost differences), but also in the uncertainty of a cost-effectiveness ranking.

Uncertainty is also something which can be captured economically: The value of having less uncertainty can be determined using value-of-information analyses, where one assigns monetary value to having better information and reducing uncertainty (Schwendicke et al. 2017; Schwendicke et al. 2018). Such studies are useful to demonstrate if further data or research is worthwhile (i.e., economically sensible), and also which kind of uncertainty should be reduced first to yield the highest economic benefit.

HEALTH ECONOMIC ANALYSIS IN ENDODONTICS

Review of the literature

To assess the existing evidence on health economics of endodontic therapies, two electronic databases (Medline via PubMed and Embase via Ovid) were screened for eligible studies. Additionally, cross-referencing from bibliographies of the included studies was conducted. Two logic blocks were combined using Boolean operators as follows for PubMed, and the search sequence adapted for Ovid: ("cost effectiveness" OR "economics" OR "costs") AND ("endodontic" OR "vital pulp therapy" OR "direct pulp capping" OR "partial pulpotomy" OR "full pulpotomy" OR "root canal treatment" OR "endodontic treatment"). A total of 192 entries were identified, and the full-text of 25 studies screened against the inclusion criteria, which were (1) an economic analysis being conducted on vital pulp therapy and/or primary or secondary non-surgical or surgical root canal treatment in (2) both primary and permanent teeth, (3) published in English, (4) without time restrictions (Figure 1). Eleven studies were included (Table 1, Appendix A).

The included studies covered four main endodontic subdisciplines: (1) endodontic procedures in primary teeth (Oliveira et al. 2021), (2) vital pulp therapy (Asgary et al. 2014; Schwendicke & Stolpe 2014; Schwendicke et al. 2015; Brodén et al. 2019; Emara et al. 2020), (3) primary root canal treatment (Balevi & Shepperd 2007; Pennington et al. 2009; Schwendicke & Göstemeyer 2016) and (4) (non-) surgical retreatment (Kim & Solomon 2011; Schwendicke & Stolpe 2015).

Different types of analyses were performed, with data stemming from two sources:

- Two studies performed cost-of-disease analyses nested within clinical trials (Asgary et al. 2014; Oliveira et al. 2021), focusing on the costs of providing endodontic therapy. One study additionally considered the costs associated with failure of the provided therapy. The data informing these studies by large stemmed from the original trials, that is, were prospectively collected.
- Seven studies performed cost-effectiveness analyses using a Markov simulation modelling approach (Pennington et al. 2009; Schwendicke & Stolpe 2014; Schwendicke et al. 2015; Schwendicke & Stolpe 2015; Schwendicke & Göstemeyer 2016; Brodén et al. 2019; Emara et al. 2020). Another cost-effectiveness study was conducted without state-transition modelling (Kim & Solomon 2011).
- One study combined cost-utility and cost-benefit analyses (Balevi & Shepperd 2007).

The reported horizon of the two clinically grounded studies ranged from 0 (Oliveira et al. 2021) to 2 years (Asgary et al. 2014). The horizon of the modelling studies varied, ranging from 5 years (Balevi & Shepperd 2007) up to the remaining lifespan of the modelled patients. The data to inform modelling studies stemmed from systematic reviews of the available literature or large cohort studies.

Several perspectives were identified; notably, three studies did not mention explicitly their chosen perspective (Balevi & Shepperd 2007; Pennington et al. 2009; Kim & Solomon 2011):

- Eight studies used a payer perspective, with costs being assessed using fee item catalogues of public and private insurances (Schwendicke & Stolpe 2014; Schwendicke et al. 2015; Schwendicke & Stolpe 2015; Schwendicke & Göstemeyer 2016; Emara et al. 2020), national average dental fees (Kim & Solomon 2011), or national tariffs (Asgary et al. 2014)
- Two studies estimated staff and resources needed and the associated costs under a providers' perspective (Pennington et al. 2009; Oliveira et al. 2021).

Findings of the studies

Five studies were related to vital pulp therapy:

- Selective caries removal was found to be more cost-effective than non-selective ("complete") removal in teeth with only mild symptoms. For managing pulp exposure, direct pulp capping with mineral trioxide aggregate (MTA) was more cost-effective than capping with calcium hydroxide (CaOH). As a result,

TABLE 1 Characteristics of the included endodontic health economic studies

Author/year	Setting	Analysis	Population	Horizon	Perspective	Clinical problem
Oliviera et al. (2021)	Brazil; public and private offices	Cost-of-disease-analysis	52 children, 3–6 years old; primary incisors	0 years	Payer	Conventional instrumentation; or antibiotic paste for endodontic therapy of primary incisors
Emara et al. (2020)	Modelled population, Germany	Cost-effectiveness analysis	30 years old men, molars with positive reaction to cold testing	Patients' lifetime	Mixed public-private payer	Selective and non-selective caries tissue removal and comparison of direct pulp capping with mineral trioxide aggregate (MTA) or calcium hydroxide (CaOH) for exposed pulps
Brodén et al. (2019)	Modelled population, Sweden	Cost-effectiveness analysis	12-year-old children; pulpal exposure due to deep caries in a vital permanent first molar	9 years	Healthcare provider	Pulp capping or immediate root canal treatment for cariously exposed pulps
Schwendicke and Göstemeyer (2016)	Modelled population, Germany	Cost-effectiveness analysis	40-year-old men; nonvital asymptomatic pulps without a radiographically detectable periapical lesion	Patients' lifetime	Mixed public–private payer	Single or multistep root canal treatment
Schwendicke and Stolpe (2015)	Modelled population, Germany	Cost-effectiveness analysis	50-year-old men; asymptomatic molars with root canal filling and radiographic finding	Patients' lifetime	Mixed public–private payer	Immediate restoration without secondary root canal treatment or secondary root canal treatment before restoration for teeth with radiographic signs of insufficient root canal treatment
Schwendicke et al. (2015)	Modelled population, Germany	Cost-effectiveness analysis	20-year-old male individuals with 1 permanent molar with a vital asymptomatic pulp and an extensive carious lesion involving 3 surfaces, with pulp exposure during excavation	Patients' lifetime	Mixed public–private payer	Direct pulp capping with calcium hydroxide versus mineral trioxide aggregate
Schwendicke and Stolpe (2014)	Modelled population, Germany	Cost-effectiveness analysis	20-year-old men; 1 permanent molar, vital, and asymptomatic pulp; pulp exposure during excavation, 3 surfaces involved	Patients' lifetime	Mixed public–private payer	Direct pulp capping versus immediate root canal treatment after pulp exposure during caries excavation

Metho-dology	Health outcome	Findings	Health outcome	Cost outcome
Multicenter trial	n/a	Treatment time and costs higher for instrumentation	n/a	(a) Antibiotic paste 6.73 USD; (b) Instrumentation 16.15 USD
Markov simulation model	Tooth retention years	Selective removal more cost-effective for caries removal; MTA more cost-effective	Retention years: (a) selective and CaOH: 37; (b) non-selective and CaOH: 36; (c) selective and MTA: 37; non-selective and MTA: 37	(a) Selective & CaOH: 2155 Euro; (b) non-selective and CaOH: 2245 Euro; (c) selective and MTA: 2140 Euro; (d) non-selective and MTA: 2176 Euro
Markov simulation model	Tooth extraction rate	Pulp capping more cost-effective	(a) Pulp capping 4.7%; (b) Root canal treatment 15.1%	(a) Pulp capping: 334 Euro; (b) root canal treatment: 701 Euro
Markov simulation model	Tooth retention years	Single visit treatment more cost-effective	(a) Molars: single visit 19.9 years; multistep treatment 19.8 years. (b) Single-rooted: single visit 18.9 years; multistep 15.1	(a) Molars: single visit 1703 Euro; multistep 1729 Euro. (b) Single-rooted: single visit 1667 Euro; multistep 1770 Euro
Markov simulation model	Tooth retention years	No immediate retreatment was more cost-effective	(a) No immediate retreatment: 25–29 years. (b) Immediate retreatment: 25–27 years	(a) No immediate retreatment: 589–954 Euro. (b) Immediate retreatment: 1163–1359 Euro
Markov simulation model	Tooth retention years	Mineral trioxide aggregate more cost-effective	(a) Mineral trioxide aggregate: 52 years. (b) Calcium hydroxide 49 years	(a) Mineral trioxide aggregate: 1368 Euro. (b) Calcium hydroxide 1527 Euro
Markov simulation model	Tooth retention years	Pulp capping more cost-effective in younger patients or those with occlusal exposure, immediate root canal treatment more cost-effective in older patients or those with proximal exposure	(a) 20 year-old-men: direct pulp capping 52 years; immediate root canal treatment 52 years; (b) 50-year-old men: direct pulp capping 27 years; immediate root canal treatment 29 years	(a) 20-year-old men: direct pulp capping 545 Euro, immediate root canal treatment 700 Euro. (b) 50-year-old men: direct pulp capping 746 Euro, immediate root canal treatment 589 Euro

TABLE 1 (Continued)

Author/year	Setting	Analysis	Population	Horizon	Perspective	Clinical problem
Asgary et al. (2014)	Iranian Center for Endodontic Research, Tehran, Iran	Cost-of-disease analysis	Healthy male/female patients 9–65 years old, irreversible pulpitis, molar	24 months	Healthcare provider	Pulpotomy versus root canal treatment in molars with irreversible pulpitis
Kim and Solomon (2011)	United States of America	Cost-effectiveness analysis	Failed endodontically treated molar after initial root canal therapy	Survival probability	Healthcare provider	(a) Non-surgical retreatment with full-coverage restoration. (b) Non-surgical retreatment with crown-lengthening and full-coverage restoration. (c) Non-surgical retreatment with post/core and full-coverage restoration. (d) Endondontic microsurgery. (e) Extraction with fixed partial denture. (f) Extraction and single implant-supported restoration for managing failed root canal treated teeth
Pennington et al. (2009)	Modelled population, United Kingdom	Cost-effectiveness analysis	Irreversibly pulpitic maxillary central incisor; loss of coronal tooth tissue was defined as sufficient to require restoration with a post-retained crown; healthy adult male of varying age; tooth restorable with post-retained crown	Patients' lifetime	Healthcare provider	How to treat a damaged incisor cost-effectively?
Balevi and Shepperd (2007)	Vancouver, British Columbia, Canada	Cost-benefit analysis	40 teachers (mean age 48.9 ± 2.55a; 75% females)	5 years	Healthcare provider	Different treatments of abscessed maxillary incisor or mandibular molars

selective caries removal combined with (if needed) pulp capping with MTA resulted in the longest tooth retention (in mean 37.37 years over the lifespan of an initially 30-year-old male individual) and the lowest cost (2141 Euro) compared to selective caries removal combined with capping using CaOH (37.22 years; 2155 Euro), or non-selective caries removal combined with CaOH (36.29 years; 2245 Euro) or MTA (37.24 years; 2176 Euro (Emara Krois et al. 2020).

Metho-dology	Health outcome	Findings	Health outcome	Cost outcome
Multicenter trial	(a) Clinical b) radiographical success	Pulpotomy less costly	(a) Clinical success: both 98.19%. (b) Radiographical success: pulpotomy 86.7%; root canal treatment 79.5%	(a) Pulpotomy: 7 USD; failure costs: 29 USD. (b) Root canal treatment: three canals 25 USD; four canals 33 USD; failure costs: 47 USD
Strategy simulation model without state transitioning	Tooth survival	Endodontic microsurgery was most cost-effective	Survival probability: (a) Non-surgical retreatment 87%; (b) endodontic microsurgery 94%; (c) fixed partial denture 89.1%; (d) single implant-supported crown 94.5%	(a) Non-surgical retreatment 944 USD general practitioner (GP), 1256 USD specialist (SP). (b) Crown-lengthening: additional costs: GP 55 USD SP 924 USD. (c) Porcelain fused to metal crown: GP 945 USD SP 1380 USD. (d) Post/core: GP 269 USD SP 398 USD. (e) Partial denture: GP 2957 USD, SP 4254 USD. (f) Single implant plus and restoration: GP 3771 USD SP 4570 USD. (g) Endodontic microsurgery GP 698 USD SP 1090 USD
Markov simulation model	Longevity of crown	Root canal treatment extended the life of a tooth and an additional cost of 5–8 pounds per year/tooth life; if the root canal treatment fails, retreatment extended life for additional costs of 12–15 pounds per year/tooth life; surgical retreatment is not cost-effective, (replacement with a single implant restoration favourable)	Longevity: (a) One root canal treatment (age 35/age 55/age 75: 15.81/12.62/7.1 years). (b) Retreatment after root canal treatment (17.29/13.56/7.41 years). c) Implant (20.12/14.96/7.74 years) d) extraction (0/0/0 years)	Expected total lifetime costs (British pound): a) One root canal treatment (age 35/age 55/age 75: 805/717/597). (b) Retreatment after root canal treatment (828/730/601). (c) Implant (1623/1570/1487). d) Extraction (731/649/540)
Standard gamble method modelled after Fyffe and Kay; willingness-to-pay (bidding algorithm)	Cost-utility ratio (quality of tooth years x survival time)	Utility highest for bridge and single tooth implant	Survival probability after 5 years: (a) Root canal treatment 90%; (b) conventional crown 95.3%;) (c) single tooth implant 95.1%; d) conventional dental bridge 94.0%; (e) removable partial denture 76.1%	(a) Post-and-core crown (molar = 2200 CD; incisor = 2000 CD). (b) Single tooth implant (molar = 3600 CD; incisor = 3600 CD). (c) Bridge (molar = 2620 USD; incisor = 2608 USD). (d) Partial denture (molar = 950 USD; incisor = 950 USD)

- If only assessing direct pulp capping (ignoring the prior caries removal strategy), another study found that MTA was more cost-effective (retention years/lifetime costs: 52 years/1527 Euro) than CaOH (49 years/1527 Euro) despite higher initial treatment costs (Schwendicke et al., 2015).
- For treating the exposed pulp, direct pulp capping or pulpotomy was more cost-effective than root canal treatment in most scenarios. In one study, direct pulp capping was more cost-effective (retention years/total costs: 52 years/545 Euro; 52 years/701 Euro) in younger patients (initially 20-year-olds) with occlusal pulp exposure than

immediate root canal treatment. For 50-year-old individuals, and proximal exposure, the opposite was found; immediate root canal treatment was more cost-effective than direct pulp capping (27 years/746 Euro; 29 years/590 Euro) (Schwendicke & Stolpe 2014).
- For 12-year-old children, direct pulp capping was more cost-effective than immediate root canal treatment within a horizon of 9 years (extraction rate/costs: 4.7%/334 Euro; 15.1%/701 Euro) (Brodén et al., 2019).
- For permanent teeth diagnosed with irreversible pulpitis in individuals aged 6 to 65 years, there was no statistically significant difference in the clinical or radiographic outcome between both pulpotomy and root canal treatment within 2 years follow-up, but pulpotomy was less costly than root canal treatment. Moreover, costs associated with failure of these initial therapies were also lower for pulpotomy than for root canal treatment (pulpotomy 7 USD, failure costs 29 USD; root canal treatment three/four canals 25/33 USD, failure costs 47 USD) (Asgary et al. 2014).

Two studies compared root canal treatment with alternatives for retaining teeth:

- Pennington et al. (2009) compared six different options: tooth preservation (non-surgical and/or surgical root canal [re-]treatment) or tooth extraction followed by a) resin bonded bridge, b) conventional bridge, c) removable partial denture d) implant-supported single crown) as a therapy for an irreversibly pulpitic maxillary incisor with significant loss of coronal tooth tissue (defined as sufficient to require restoration with a post-retained crown) in adult males. Retaining teeth over the entire lifespan of a patient using root canal treatment was a cost-effective intervention with additional costs of 5–8 GBP per year (depending on the initial age of the patient) compared to removing and replacing the tooth with a bridge or partial denture (Pennington Vernazza et al. 2009). Orthograde retreatment was also found to be possibly cost-effective (additional costs per year: 12–15 GBP) compared with replacing teeth using single implants (57–241 GBP).

In contrast, Balevi & Shepperd (2007) found that for managing permanent molars or incisors with an abscess, the expected-utility-values were lower for root canal treatment followed by the placement of a post-and-core crown (molar 6.9/incisor 5.27; costs: molar 2200 CND/incisor 2000 CND) than those for a single tooth implant (9.51; 8.35; 3600 CND/3600 CND).

For managing teeth with non vital pulps, a number of studies were available:

- Single visit root canal treatment was found to be more cost-effective than multivisit treatment (tooth retention years single visit/multistep: molar 19.9 years /19.8 years, single-rooted 18.9 years /15.1 years; treatment costs: molar 1703 Euro/1729 Euro, single-rooted 1667 Euro/1770 Euro) (Schwendicke & Göstemeyer 2016).
- For molars which had been root canal treated before, were asymptomatic but had radiographic risk factors for failure (e.g., persistent periapical pathosis, under- or overextended root canal filling), and had been only temporarily restored and now needed permanent restoration, immediate secondary root canal treatment (tooth retention years/costs 25–27 years /1163–1359 Euro) before placing the definitive restoration was not cost-effective compared to restoring the tooth without secondary root canal treatment (25–29 years /589–954 Euro) (Schwendicke & Stolpe 2015).
- The data for surgical retreatment were heterogenous: Pennington et al. (2009) reported that surgical retreatment was not cost-effective as a second-line intervention and recommended orthograde retreatment instead (Pennington et al. 2009).
- On the other hand, Kim and Solomon (2011) found that surgical retreatment was more cost-effective than orthograde retreatment for root filled molars with post-treatment disease (Kim & Solomon 2011).

Overall, the body of evidence towards the health economics of endodontic therapies was heterogenous and suffered from a range of limitations: Not all studies identified robust data to inform their analyses or could support the required assumptions (during modelling) with sufficient evidence. If data from more robust sources such as clinical trials were available, these trials often reported only short- or mid-term outcome data – whilst for modelling, long-term outcomes are of interest. Consequently, many analyses relied on a wide range of assumptions, which had to be tested for their impact in sensitivity analyses. It is further relevant to highlight that the context and perspective (e.g., a payer's perspective in a specific healthcare system) will determine the generalizability of the individual studies, and that in the included studies, a comprehensive assessment of costs (i.e., societal perspective) was not undertaken.

From this review, a number of themes were identified:

- Maintaining pulpal vitality is preferable over root canal treatment if possible when it comes to cost-effectiveness. First, all attempts should be made to avoid a pulp exposure during caries removal in teeth without pulpitis or with initial pulpitis only. When it comes to a pulp exposure, direct pulp capping or pulpotomy was more cost-effective than an orthograde root canal treatment.
- Retaining teeth using root canal treatment is usually more cost-effective than removing and replacing teeth (Pennington et al. 2009).

- More invasive interventions such as retreatments should be indicated with caution in asymptomatic cases, as cost-effectiveness may not be valid.

A CALL TO ACTION

The relative paucity of robust clinical data with mid- or long-term outcomes in endodontics also impacts on endodontic health economic analyses (Lucena et al. 2017; Duncan et al. 2020). The heterogeneity in study conduct and outcomes hampers data synthesis and further limits the options for robust economic evaluations (El Karim et al. 2021; Nagendrababu et al. 2021). The general sparsity of economic analyses on endodontic interventions is worrisome, as decision makers such as commissioners or payers increasingly rely on such analyses. The endodontic community is called for action to improve the competency of both researchers to plan and conduct such studies, but also clinicians who should consider health economic factors when assigning interventions. Health economics should become an accepted pillar of endodontic research (Rabarison et al. 2015), and introducing new techniques and methods in endodontics should go hand in hand with economic analyses as part of a detailed assessment of acceptability and implementation.

CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this study.

ACKNOWLEDGMENT

Open Access funding enabled and organized by Projekt DEAL.

ETHICS STATEMENT

There was no ethical approvement necessary for this article, because no human or animal experiments were involved.

AUTHOR CONTRIBUTIONS

The study was conceived by FS and SRH. FS and SRH lead the investigation including literature review, evaluation and validation. FS and SRH wrote and approved the manuscript.

DATA AVAILABILITY STATEMENT

No original data was collected or needs reporting for this article.

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How to cite this article: Schwendicke, F. & Herbst, S.R. (2023) Health economic evaluation of endodontic therapies. *International Endodontic Journal*, 56(Suppl. 2), 207–218. Available from: https://doi.org/10.1111/iej.13757

APPENDIX A

Author/year	Title	Reason for exclusion
Ivica et al. (2021)	Therapeutic potential of mesenchymal stem cell-derived extracellular vesicles in regenerative endodontics	No cost-effectiveness/cost analysis
Andrade (2021)	Cast metal posts versus glass fibre posts: which treatment of choice based on cost-minimisation analysis?	Post-endodontic restoration
da Silva et al. (2020)	Cost-effectiveness analysis of rehabilitation interventions for teeth with extensive coronary destruction	Article in Portuguese
Li et al. (2019)	Pulpotomy for carious pulp exposures in permanent teeth: A systematic review and meta-analysis	No cost-effectiveness/cost analysis
Bjørndal (2019)	Is pulpotomy preferable to root treatment where there is pulp exposure?	No cost-effectiveness/cost analysis
Koch et al. (2012)	A cost-minimization analysis of root canal treatment before and after education in nickel-titanium rotary technique in general practice	No cost-effectiveness/cost analysis
Kinra (2011)	Endodontic quality: at what cost	No cost-effectiveness/cost analysis
Kim & Baek (2004)	The microscope and endodontics	No cost-effectiveness/cost analysis
Kvist (2001)	Endodontic retreatment. Aspects of decision making and clinical outcome	No cost-effectiveness/cost analysis
Chawla (1998)	Scientific rationale and cost effectiveness of routine use of rubber dam in clinical practice	No cost-effectiveness/cost analysis
Schürmann (1989)	Direct pulp capping from the economic viewpoint	No cost-effectiveness/cost analysis
Siskin (1963)	Economics, indications and contraindications for endodontic therapy	No cost-effectiveness/cost analysis