Value of root-filled teeth in maintaining a functional dentition for life

K Gulabivala & Y-L Ng

Introduction

Modern values place an increasing importance on retention of teeth, whether for aesthetics, function or quality-of-life[1] even though they may be regarded by a proportion of the populace as an organ of lesser importance to survival, being individually disposable by virtue of numbers and distribution in the mouth. Replacement options for lost teeth had traditionally focused on removable dentures or fixed bridges but recently, fewer lost units and relatively intact remaining teeth, coupled with the availability of implant-retained crowns and bridges have completely revised the dynamic of this dialogue. Not only have implant-retained prostheses gained predominance in the discussion[2,3] but they have altered the threshold for retention of “compromised”, and worryingly, not so compromised teeth[3]. The speed and extent of this revision has been based on an unrealistic optimism about the predictability, survival, success and utility of implants *in every scenario*[4]. The reality is that implants like any other restorative option, suffer from their own disadvantages, including unsuitability for certain sites or patients, primary failure of fixture integration, secondary failure of established integration, failure of mechanical components, peri-implantitis and other less frequent morbidities[5-7].

In common with pendulum swings that are a normal part of various life events or natural homeostasis, common sense will hopefully prevail, and the flux will again be towards retention of teeth, as far as tooth structure integrity and periodontal health allow[8]. Implant options should be viewed much like any other, with their pros and cons, in context-specific ways[2], and do not hold any superiority, *per se*, over well-restored root-treated teeth[9-11]. Unfortunately, the readily available internet sources may not sufficiently inform patients adequately on the choices available[12]. It is therefore upto the dentist to provide appropriate counsel as part of proper informed consent.

Long-term strategic planning for maintenance of a functional dentition

The purpose of this article is to draw attention to the strategic goals of planning for a functionally and aesthetically optimal dentate quality-of-life, and the role that teeth maintained through root canal treatment can play in such a plan. The perception that root-treated teeth should largely, and wherever possible, be discarded as a viable option is a seriously flawed judgment. The utility of root-treated teeth must be properly and critically discriminated as they *can* play a significant role in the long-term plan, despite having unique characteristics that must be accounted for.

Teeth may be lost because of poor prognoses related to unrestorability (loss of tooth structure through caries, tooth wear, fracture), loss of periodontal support, persistent infection (periradicular) or persistent pain/discomfort[13,14]. Any replacement plan should be cognizant of the primary cause of the loss and account for its future contribution to failure of the replacement or remaining teeth. That is, primary disease or cause-predilection must, first be controlled[15,16].

In certain scenarios, even lack of restorability may not be the final arbiter in the decision to extract a root-treated tooth or root because it may still help preserve anterior soft tissue aesthetics[17], maintain occlusal space, support an over-denture, and or maintain bone height and volume for later implant replacement in young patients[18].

The average human life-expectancy in the UK is around 80 years (https://www.kingsfund.org.uk/publications/whats-happening-life-expectancy-uk). The peak decade in which restorations and teeth begin to fail is in the age-group 40-50's[19], which means that even in the best case-scenario, on average, it is still necessary to budget for functionally dentate survival for another 30-40 years. Studies on the longevity of restorations may follow cohorts for 5 (short-term), 10 (medium-term)[16] or 20 (long-term) years in rare cases[20] and therefore quote percentage survival (still existing with interventions), success (still existing without intervention) or annual failure rate (AFR) over these terms[21,22]. It is therefore wise to budget for failure of any restorative modality and consider the impact of failure on the next option. In this context, selection of the most conservative option first, should leave further restorative options open for later in life, when it may become harder to adapt to change[23] and when perhaps success rates diminish[24-26]. If a restorative modality can predictably (80% plus probability) offer 5-10 years of function before the next most radical option needs to be considered, it can be said to have made a valuable contribution in the health cycle[27,28]. The utility of the restoration extends beyond function and aesthetics to the time accrued for the patient to acquire the means to pay for the more radical options later in life. Restoration of the root-treated tooth should achieve satisfactory aesthetics, form and function, while preserving and protecting the maximum amount of remaining tooth structure[29,30] and alveolar support.

The case for predictability of endodontic treatment

The principles of root canal treatment were established long ago[31] based on the notional aetio-pathogenesis of apical periodontitis and the intuitive premise that controlling intra-radicular infection would calm or switch-off the pro-inflammatory stimulus. Chemo-mechanical preparation[32] and obturation to guideline standard[33] have served well and predictably to control infection and periapical inflammation[34], yielding respectable published clinical healing rates of 70-90%[35,36]. The long duration required to secure the certainty of complete periapical healing[35] is due to the nature of interaction between residual microbiota and host tissues[37,38]. Nevertheless, given guideline standard treatment and absence of symptoms, periapical healing dynamics eventually progress towards complete resolution, for most (91%)[39], within 1-2 years but in a smaller proportion (6%) taking upto 20-27 years[40]. Delayed healing may be influenced by extruded material[40] or gene polymorphisms in inflammatory and wound healing events[41].

Technological advances in the last two decades have made root canal treatment more efficient and brought it within the technical reach of many more general dental practitioners[43-45], although without necessarily improved periapical status[35,45]. Nevertheless, clinical outcome studies have helped forge a clearer understanding of the factors influencing positive outcomes.

Treatment factors having a major impact on favourable root canal treatment outcome are: apical proximity of instrumentation (and thus irrigation) and root filling to the canal terminus, avoidance of root-filling extrusion, negative microbial culture result prior to obturation, quality of root-filling (surrogate measure of quality of entire procedure), and quality of the final coronal restoration[39].

Post-treatment disease can be predictably managed by root-end surgery using a contemporary approach[46-49], achieving a 94% (95% CI: 89%, 98%) pooled healing rate. Unlike non-surgical root canal treatment, advances in technology *have* resulted in improvement of the quality and outcome of root-end surgeries over the last two decades. Treatment factors having a major impact on favourable root-end surgery outcome are: use of magnification, root-end resection with minimum bevel, use of ultrasonic tip for retro-cavity preparation, and retrograde filling material such as mineral trioxide aggregate cement (MTA), Super-ethoxybenzoic acid cement (EBA), or Intermediate Restorative Material (IRM). The healing dynamic after root-end surgery is faster than non-surgical root canal treatment and most successful cases heal within two years[50,51].

Case for predictable survival of root-treated teeth and factors affecting mode of mechanical failure of susceptible teeth

Despite the clinical reputation for inherent weakness in strength of root-treated teeth, 91% survive at 2-3-years and 87% at 8-10-years. Loss of the small proportion of such teeth failing may be precipitated by un-restorable caries (22%-61%)[25,52-54], endodontic problems (29%), tooth fracture (29% – 36%) or restoration failure (23%)[25,53-57]. The distribution of susceptible teeth is uneven amongst tooth types.

Tooth type, location and restoration type combine to significantly influence survival of root-treated teeth. Root-treated molars with both, mesial and distal adjacent teeth missing, or those that are last-standing in the arch, exhibit a higher risk of loss[15,16,55,56,58]. Restorative factors having an important impact on survival of root-treated teeth include presence of cracks [59], amount of residual coronal dentine[60,61], type of coronal restoration[15,56,58,62,63], deployment of root-treated teeth as abutments[55,58,62,64] and periodontal condition[65]. Placement of crowns or cast overlay restorations may improve molar tooth survival[15,25,55,56,58,62,63].

The *higher* propensity of fracture of root-treated immature anterior teeth[66] and premolars with mesio-occlusal-distal (MOD) plastic intra-coronal restorations is well-documented[67-69]. The distribution of stresses within residual tooth structure is dependent upon the tooth type and pattern of remaining structure, as well as the restoration design. Mechanical failure may occur at any weak juncture and spread, rapidly (catastrophically) or slowly. Tooth cracks have been known to propagate slowly over many years (upto 10 years)[59].

The incidence of cusp fracture ranges from 21[70] to 73[71] per 1,000 person-years. The incidence is higher in molar teeth and those with more restored surfaces[70]. The prevalence of cusp fracture of root-treated teeth is given in table 1.

Stratified analyses reveal the highest prevalence of fracture amongst root-treated posterior teeth restored with glass ionomer cement (37%) or amalgam (30%), compared with composite (8%) or partial veneer restorations (0%) after 16 years[75], although the choice of restoration may have been dictated by the amount of remaining tooth structure, in the first place. The prevalence of tooth fracture in posterior root-treated teeth increases from a range of 17% – 25% for those with two or less surfaces missing, to a range of 29% – 36% in teeth with three or more surfaces missing[75]. Root-treated teeth may also fail through root fracture, which range in *prevalence* from 1% to 4%, with no obvious difference amongst teeth with various extents of tooth structure loss or restoration type[61,67,74,76] (Table 2). In contrast, the *incidence* rates range between 0% and 37%, and increase with the amount of tooth structure missing [61].

Three main reasons are advanced to explain the possible susceptibility of root-treated teeth to fracture: 1) loss of integrity or weakness in the coronal tooth architecture[67,77-84]; 2) altered mechanical properties of dentine[85-93]; and 3) altered proprioceptive feedback[94-98].

Restorative planning should aim to mitigate these factors as far as possible; that is, avoid unnecessary removal of tooth structure by selecting the most conservative restorations, avoid or minimize dentine-damaging strategies and avoid pulp de-vitalisation, where possible.

Effect of chemo-mechanical root canal debridement on the mechanical properties of dentine

Despite the absence of a substantial catastrophic effect of root canal treatment on long-term tooth survival, laboratory studies show clear effects of the procedure on properties of dentine and teeth. The procedure can lead to changes in the physical[99], mechanical[100-102], and chemical [103-105] properties of dentine.

NaOCl denatures or dissolves the collagen in dentine[103,105-109], leading to a reduction in elastic modulus, microhardness, flexural strength[100,110] and visco-elasticity, as well as an increase in strain upon loading of dentine or whole teeth[102,111]. Demineralising agents, such as EDTA or other acids, do not affect collagen, *per se*[103-105] but disrupt the inorganic matrix and expose the collagen fibrillar structure to further damage from NaOCl[103,108,109,112]. The synergistic effect of combining NaOCl and EDTA, leads to a greater change in dentine, than either agent used in isolation[103,105].

Heat from warmed irrigants, thermplasticised gutta-percha and rotary instruments may cause loss of unbound dentine water through evaporation, as well as loss of bound water at temperatures above 200°C[86]. The important contribution of water to the viscoelastic properties of dentine[113] means its loss could alter the mechanical properties of teeth[89,91,114]. However, there is no definitive proof of permanent dehydration of teeth in the hydrated environment of the mouth. Collagen structure is altered to different extents at different temperatures (20-200°C) and is influenced by hydration and physical confinement within mineralized tissues[115-121].

Although there is no doubt about the potential damaging effect, the precise depth of such dentinal damage due to irrigants, had until recently been unclear. Ramirez-Bommer et al. (2018)[103] found that dentine exposed to NaOCl reduced the collagen content within the first four minutes of reaction, leading to a plateauing effect, thereafter. Conversely, EDTA continuously reduced the phosphate content of dentine over twenty-four hours and exposed the collagen content in the process. The depth of hypochlorite reaction was 16 μm after 10 mins exposure, whilst the depth of EDTA reaction increased with duration of exposure (19 µm by 10 minutes, 27 µm by 60 minutes, and 89 µm by 24 hours). NaOCl/EDTA/NaOCl alternated treatment resulted in an estimated further 62 µm of loss. Morgan et al. (2019)[107] showed the depth of effect of NaOCl irrigation in teeth, *in situ,* extended to only 0.5 mm into the dentine from the root canal wall.

The depth of effect of irrigants on dentine collagen may be a function primarily of penetration along dentinal tubules but secondarily and over longer time periods as a function of inter-tubular matrix degradation. Any weakening effect of NaOCl and EDTA on dentine[100-102,110,111,122], is likely due to the combined effect of local dentine damage coupled with altered tooth geometry through preparation[102,123]. The extent of any tooth weakening would be dictated by the breadth and depth of chemical changes in dentine during root canal irrigation, relative to the remaining bulk of unaffected dentine[102,103]. Therefore, bulkier, mature (but not old) teeth would bear the effect better than those with thin dentine walls and wide dentinal tubules. Retaining, preserving and protecting the bulk of dentine is therefore crucial in the restorative management of root-treated teeth.

Timing of restoration after endodontic treatment

The decision to place expensive coronal restorations on teeth immediately after root canal treatment is difficult when there is uncertainty about the outcome. It may take at least one, if not several years for a periapical lesion to heal but it is neither practical, nor desirable, to wait this long before a permanent restoration is placed. Indeed an early permanent coronal seal is an important final stage in the completion of root canal treatment, so as to protect and seal the root-canal system from recontamination and ensure success[63,124,125]. It is even suggested that an indirect restoration within 6 months of the root-filling has a higher survival rate than those restored with a direct restoration[26], although this observation is not universally supported. Fortunately, the mean success rate of *guideline-standard root canal treatment*[33] is high (85%), therefore it remains only for the clinician to judge whether the tooth is likely to fall into the 15% failure group. Persistent symptoms and signs of infection, lack of apical patency during treatment, large periapical lesions, extruded root-filling material, pre-existing crack(s), superimposed periodontal involvement and tooth resorption, may all signal the teeth that may fall into this group[39,56]. A small proportion of asymptomatic teeth with a higher probability to fail may be missed. It is therefore not necessary to review the tooth for longer than one month before providing the permanent restoration, *if guideline standard root canal treatment has been provided*[33]. During this time, there should be an absence of inflammation of the adjacent soft tissues, tenderness to palpation, sinus or to pressure and percussion of the tooth. Any tooth with an uncertain postoperative endodontic status may require a longer review period prior to restoration but under such circumstances a good access seal is still mandatory[63].

Principles of restoration of root-treated teeth

The general principles governing restoration of any teeth, also apply to root-treated teeth but in addition, special attention must be paid to two factors to extend longevity: 1) *preservation of as much remaining tooth tissue as possible*; and 2) *reduction of occlusal stress and its favourable distribution within the remaining tooth tissue*. The most conservative restoration design compatible with acceptable aesthetics and function should, therefore be selected in conjunction with informed patient consent.

Impact of occlusal loading on restorative considerations

The type, duration (function *versus* parafunction) and extent of occlusal loading influences the prognosis of teeth and its restorations[21]. The biomechanics of anterior and posterior teeth are fundamentally different. Anterior teeth serve an incising and tearing function and guide mandibular excursions. Their greater bulk in the facio-lingual plane provides strength in this direction of loading. Posterior teeth serve a crushing and grinding function and have a broad rectangular base with multiple roots, which may also be broad facio-lingually. They generally bear axial load, although this also resolves into lateral forces[126]. In addition, interferences in excursive movements of the mandible can jar and damage teeth, predisposing them to cracks and fractures[127]. Anterior and posterior teeth therefore merit unique restorative considerations.

The degree of occlusal loading on teeth is assessed subjectively from a triangulation of clinical observations, including history of breaking restorations or teeth, evidence of attrition, abfraction, mobility, drifting and the size and activity of muscles of mastication. Occlusal loading is difficult to control clinically because it is dependent not only on the nature of occlusal contacts but also on eating, chewing and parafunctional habits and state of the masticatory musculature. Design and control of the closure contact and intercuspal and excursive relationships of teeth can help to achieve a measure of control that is not absolute. Excursive occlusal contacts should generally be avoided on root-treated teeth if possible, and preferentially transferred to adjacent vital and/or more robust teeth.

Restoration design is dictated by the residual tooth structure distribution, properties of the selected restorative materials and the occlusal and aesthetic demands of the individual. The dissemination of forces within the reconstructed “system” (tooth/root, core, crown) should be intuitively estimated. Accounting for this triumvirate, combined with meticulous execution of the clinical procedures should offer a successful and predictable restoration. It is intuitively evident that a root-treated tooth serving as a single independent unit will experience different levels and patterns of stresses than one absorbing a larger occlusal load, such as a bridge or denture abutment[64,128,129].

Restorability, integrity and distribution of remaining tooth structure and available restorative space

Within limits, any remaining tooth structure can be “restored” but this is very different from providing a “*predictable restoration*”, which offers the patient a measure of certainty about the longevity and functionality of the restoration. “Predictable restorability” of the tooth should be determined before endodontic treatment, as part of a general restorative and oral treatment plan. Teeth with existing cracks offer the worst long-term prognosis and predictability, particularly when such cracks extend to the pulpal floor and are associated with a periodontal defect[59,130]. However, teeth free of such defects and displaying sufficient remaining tooth structure offer good scope for supporting a lasting restoration[131,132]. The remaining tooth structure may be sculpted into a shape providing adequate retention and resistance form for a restoration, depending upon its amount and distribution. Where the amount of remaining tooth structure and its distribution preclude adequate retention and resistance form, it may be supplemented with a core material to facilitate restoration. Retention of the core material, though, is conditional upon sufficient tooth structure, pulp chamber integrity or root structure to aid its retention. Although it is difficult to prescribe strict thresholds, a cast restoration encompassing at least 2 mm (in height and width) of sound dentine around the tooth circumference (ferrule) makes the longevity of the restoration more predictable[132-135]. In the absence of sufficient coronal tooth structure, retention may be gained from the root by deploying a dowel or post. It is critical to evaluate the length, width, shape and curvature of the root, to assess the potential for placing a post.

Each type of restoration demands a minimal amount of space for the chosen restorative material to provide optimal occlusal strength and contours. Different materials, depending on their mechanical properties, require different amounts of space. This will naturally be at the expense of remaining tooth structure or available inter-occlusal space and so the most conservative designs should ideally be chosen, consistent with the patient’s needs. Broken down teeth requiring endodontic treatment may have allowed adjacent teeth to drift and occupy its occlusal and proximal space, rendering the residual space unrestorable; the availability of adequate space must be assessed beforehand.

A successful restoration design, apart from being well-executed, will have coherently accounted for a harmonious synchrony of space, residual tooth structure, material of construction, aesthetic and functional requirements and occlusal loading.

Restoration of anterior root-treated teeth

Relatively intact anterior teeth requiring root canal treatment pose no difficulty in restoration other than to secure an access cavity seal using composite restorative material. The belief that such *intact* teeth should be ‘reinforced’ by placing a bonded post to better distribute forces to the root is miss-placed[136-138]. The concept is flawed on two grounds, first the potential for an immediate or durable bond is uncertain[139], and secondly, the act of post preparation removes dentine and weakens the tooth further[132,140]. The amount and distribution of remaining coronal tooth structure positively influences the survival probability of teeth with posts[136]. If the fracture toughness of the tooth structure is exceeded because of post placement, the resulting fracture is more likely to be located in the root and thus be more unfavourable[141]. The location of fracture is also affected by the stiffness of the post, the stiffer the post, the more apical the transmission of forces and hence more unfavourable the fracture[142]. The need for a post is a clinical judgment based on the estimated amount and distribution of remaining dentine after the tooth is prepared for the selected restoration. If sufficient dentine core remains for crown placement after preparation, then post/cores are unnecessary[136-138].

Relatively intact root-treated anterior teeth sometimes require labial reconstruction to create an impression of realignment or mask discoloration not manageable by bleaching alone. Under such circumstances, the most conservative restoration able to satisfy aesthetic and functional demands should be chosen to avoid weakening the tooth. Optimal restorative materials include composite or porcelain veneers. Full ceramo-metal or ceramic crown designs are more destructive and in small teeth (maxillary lateral and mandibular inciors) predispose them unnecessarily to the need for a dowel, which in any case, they may not be able to support.

Predisposition to proximal caries and its management leads to the presentation of root-treated anterior teeth with a “band” of missing tooth structure across the middle of its crown. If the labial enamel plate is intact, strong and unblemished, such cavities should be restored with composite restorative materials[137]. Only significantly tainted labial enamel or additional extensive cavities, restorations or tooth surface loss would strengthen the case for full coverage indirect restorations.

The anterior tooth prepared for full coverage restoration should be assessed to review the need for supplementation with a post/core. Remaining coronal tooth structure, wherever possible, should not be sacrificed for the convenience of a smooth “roof-top” preparation, rather it should be preserved and *supplemented* with the artificial core material to provide a more conservative design with some element of a ferrule[132,135].

The volume of literature on posts is truly prolific and has been systematically reviewed by many groups, giving different perspectives and findings (Table 3).

The number of systematic reviews has also prompted their assessment using R-AMSTAR, revealing a lack of methodological quality[151] but nevertheless, their findings give some intuitive insight about the available data.

Contradictory and some negative clinical survival data on posts may have contributed to the overall unfavourable perception of their utility but as table 3 shows, posts can and do work, the problem is to define the conditions under which optimal performance can be predictably assured. Individual studies on post or tooth survival stratified by study design are listed in table 4 along with key findings.

Directions for a favourable outcome of using posts are offered here based on clinical experience coupled with an intuitive synthesis of the available literature. Posts may be selected from a range of prefabricated designs or be custom-made based on their properties of retention, stress distribution, ease of application, predictability and cost. The characteristics influencing retention and stress distribution include material of construction, shape, length, diameter and surface configuration.

The traditional material of construction was cast gold, supplemented with a wrought gold post if conditions of stress or post dimensions demanded but they may also be made of stainless steel, titanium, base metal alloys, ceramic (zirconia), and carbon or glass-fibre. High-strength ceramics, such as zirconium, have been used for prefabricated posts and glass-infiltrated aluminum oxide ceramics have been used for custom-made post and core constructions. They offer high strength and in the view of some, better aesthetics. Although zirconium posts are as strong as titanium with a higher stiffness[163], their use should be selective because of their susceptibility to microcracks with aging or inadequate handling[164]. In addition, bonding to zirconium is difficult and sensitive to fatigue[165]. There are still no long-term clinical results but the removal of such posts may pose difficulty.

Posts were traditionally deemed to require high tensile strength and Young's modulus, with prefabricated metal posts performing superiorly in this respect. However, much of the recent literature focusses on the matter of choice between metal versus fibre posts; the latter deemed to have lower strength and elastic moduli, more favourable for dissipating the forces within the post rather than within the root dentine. The choice of metal or fibre posts by dentists also seems to be under peer influence as most in the USA favour fibre posts[166], whilst the majority of Australian Prosthodontists favour cast metal posts[167].

The reviews generally conclude that provided good restorative principles are strictly adhered to, there is no difference in the survival of either metal or fibre posts over the short or medium terms, when sufficient tooth structure and a ferrule exists. In the absence of a ferrule, metal posts fare better but concentrate stress in the root[168], therefore when the fatigue strength of the root is exceeded, fracture propagation in the root is the likely outcome. In contrast, fibre posts tend to generate lower stresses within the root[169] but have higher fracture indices, making them more likely to fail by loss of retention or fracture, allowing the root to be restored further, if clinically deemed appropriate.

Debonding of fibre posts highlights the issue of its adhesion to root dentine. Several procedures enhance bonding to the post, such as sandblasting or etching with different agents, followed by silanization[170]. Two other approaches to counter the problem of post adhesion include, either to use a special post containing an unpolymerized matrix[171] or a woven band of high-molecular-weight polyethylene fibers soaked with light- or dual-curing resin, folded and placed in wide post spaces[172,173]. Adhesively luting to the root dentine is even more variable than to the post surface. Success rates of 65%[174] to 90%[173,175] are reported after 7 years of service with no root fractures observed in the latter two studies.

The fracture resistance of different brands of fibre posts may be correlated to their fiber content[174]. Over the longer time-frame, posts may show an increasing propensity to fail through fatigue mechanisms in either, the root or the post, manifesting incipient cracks, loss of retention, development of periodontal pockets, abscess, pain or catastrophic fracture. Broken posts may be retrievable using a variety of methods, including ultrasonics if root canal retreatment is needed; fiber posts may be easier to remove[176].

Posts, regardless of construction material, may be parallel-sided or tapering, the former provide better retention per unit length than the latter, whilst an increase in taper reduces retention. The stress-distributing characteristics of the two designs differ between installation and functional loading. Tapered dowels generate less stress during cementation than parallel-sided dowels, however, the latter perform better in function.

Longer posts provide better retention and stress distribution for all types of posts in function but this does not mean that long roots must house equally long posts; posts only need to be long enough to provide sufficient retention, additional length inevitably causes complications of fatigue fracture or perforation. There are greater installation stresses with longer, particularly parallel-sided posts, although this can be eased by venting the post. A guide to optimal post length is that it should match the length of the crown. Other clinical yardsticks include ‘fractions of root length (1/3, 1/2 and 2/3)’ and ‘extending into the periodontal housing’. This latter point is particularly important as bone loss significantly increases the stress concentration and strain values in the root dentine and surrounding cortical bone[177].

In reality, the overall length of the root, its transverse morphology and curvature would limit the maximum extent of a post but most importantly, the impact of post length must be weighed against anticipated occlusal loading. The need for a minimum length of root filling (3mm) may also limit the achievement of optimal post length if the root is of insufficient length to accommodate both. Under such circumstances the length of one or the other needs to be sacrificed; the choice is a matter of clinical judgment but is likely to favour post-retention.

The minimum diameter of the post is determined by material of construction based on its strength to resist deformation but in the absence of a circumferential dentine ferrule for the coronal restoration, even wide posts may fracture through long-term cyclic fatigue. The diameter of a *cast* post would need to be greater than that of a *wrought* post to provide equivalent strength, therefore narrow roots benefit from wrought metal posts. Wider posts may provide marginally better retention because of increased surface area but by the same token leave thinner and weaker residual root dentine, making it more prone to fracture. It is recommended that post preparation is maintained as narrow as compatible with adequate post strength.

Posts may have smooth, roughened, serrated or threaded surface characteristics, with or without a vent to allow cement escape, which may influence seating and retention. Rough or uneven surfaces, when locked into a thin luting cement of high compressive strength increase retentive capacity. Threaded posts on the other hand provide macro-mechanical retention, which is the highest per unit length of all surface features. Prefabricated posts with a variety of thread designs are available, including their distribution along their entire length or to a restricted portion. Threaded posts generate the greatest stresses both on installation and on occlusal loading; such stresses are alleviated by pre-tapping the threads before placement to loosen the fit; the "relative lack of fit" is then managed by cementing the post. Serrated posts are also associated with increased stresses but to a much lesser extent. Improved retention from serrations and threads should be weighed against the increased stress concentration. The surface of the post may also be modified with cutaway portions or channels to provide escape routes for luting cement during installation and allow better seating and improved retention.

The cost-effectiveness of different post-retained restorations was assessed by Schwendicke and Stolpe (2017)[27] using a mixed public-private funding perspective within the German healthcare system, incorporating complication risks from systematic reviews. Using Monte

Carlo simulations in a Markov model to estimate life-time costs and tooth retention times, they concluded that prefabricated metal posts were suitable for retaining restorations, whilst glass-fibre posts may help retain teeth for longer. Cast metal and carbon-fibre posts were deemed effective but not cost-effective.

Post-hole preparation and post cementation

Placement of the final restoration after completion of root canal treatment should follow with minimal delay to reduce the risk of bacterial leakage. Immediate preparation of the post space is preferred because the dentist is already familiar with the canal anatomy and the root canal sealer will not yet have set, so the root-filling seal would not be disturbed[178]. This does not however mean that the entire root canal system need *not* be filled; the governing principle is that the entire root canal system *must always be fully obturated* before preparing the post-hole to obviate the risk of recontamination.

Aseptic conditions are imperative during post-space preparation and rubber dam isolation is the preferred method. If this is not possible, there must be adequate moisture control and the post-space should be irrigated with antiseptic solutions such as sodium hypochlorite, chlorhexidine or alcohol.

Root-filling material is first removed safely using a heated instrument before post preparation. The next step is the use of rotating instruments to enlarge the canal if the post's diameter exceeds that of the root filling. It is safest to use drills with a non-cutting tip (Gates Glidden or Peeso). The post-hole should ideally be prepared with minimal removal of dentine, yet allow adequate bulk of post to give it sufficient strength. Post-hole drilling instruments are mostly parallel-sided and rarely tapered, which creates an immediate conflict with the root anatomy given its non-uniform taper, diameter and propensity for curvatures. A slow and gentle preparation technique, cognizant of the potential for over-weakening, cracking or perforating the root must be deployed. The drills are used in ascending diameters at low speed to avoid excessive heat. As soon as the rotating instrument has evidence of cut dentine in its flutes over most of its circumference, the corresponding drill of the post system is used. These drills often have end-cutting tips so they must be used carefully and only for the final preparation, to avoid perforations.

The retention of a well-fitting post depends more on shape, length and surface roughness than on the cementing agent. The luting agent, by definition, fills the gap between post and dentine wall to transmit forces between the two. The classical luting agent for fixed restorations was zinc phosphate cement with the longest clinical evidence (and still the authors' choice) but there has been a shift towards resin composite[166,167] or resin-modified glass ionomer cements[166]. Resin cements are required for adhesive luting of fiber posts but require adequate dentine pretreatment for management of the smear layer that is always present on mechanically treated dentine surfaces; manufacturer's instructions must be followed closely.

Restoration of posterior root-treated teeth

Posterior teeth suffer the consequences of non-axial loading to a greater extent than anterior teeth and more often require occlusal protection[60,128] to stave off cuspal (Table 1) or vertical (Table 2) fractures. However, this does not mean that all root-treated posterior teeth *must be* crowned or restored with a cuspal coverage restoration (Table 5) as confirmed by three systematic reviews[20,131,179]. They did, however, conclude that the current evidence base was not strong enough to give direct and specific guidance, leaving clinicians to continue to make judgments based on clinical experience, coupled with intuitive synthesis of the literature. This means that studies provide an idea of direction of effect but sometimes they may be contradictory; it therefore requires a critical mind to rationalize the picture, judge what to make of the evidence, and how to apply it. The factors strongly influencing predictable outcome are the amount of remaining dentine and the type and quality of execution of the interventional procedure. Individual studies following various approaches to restoring posterior root-treated teeth and their findings are presented in Table 5. It shows that most approaches can work but the problem is to tease out the key principles in gaining best predictability for a given scenario.

Directions for a favourable outcome from restoring posterior root-filled teeth based on clinical experience coupled with an intuitive synthesis of the literature are offered here, using the principles stated above. Classical clinical presentation scenarios, such as access cavity only, access cavity plus proximal boxes, access cavity plus proximal boxes with variations in cuspal loss, are posited, with an analysis of the pros and cons of adopting different restorative materials and techniques to solve the restorative problem.

Intact teeth with only an access cavity

Root-treated posterior teeth presenting with nothing more than an occlusal access cavity may reasonably be restored with amalgam or composite material to seal the access. As long as there is *no evidence of cracks or signs of heavy occlusal loading* on the tooth, cuspal protection should not be required and a full crown should be considered unnecessary.

Signs of heavy occlusal loading, including cracks and facets may suggest the need for cuspal protection, in the form of full *occlusal* coverage, that is, without a full crown. The need for a fuller crown is dictated by the degree of axial surface bracing required, as indicated by the apical extent of any visible vertical cracks[184]. If only occlusal protection is required, the most conservative choice would be a metal onlay using the access cavity for retention and resistance form; adhesive techniques may aid the final outcome[30]. Precious metal alloys may be heat-treated to enhance adhesion. A tooth-coloured option may include a high strength ceramic onlay [185] but would require greater thickness and therefore occlusal reduction, as would composite material[21] to prevent restorative material chipping, fracture or marginal deterioration[185]. Adhesive retention of cuspal coverage restorations is certainly advantageous and reduces the demands on tooth preparation, although sufficient resistance form must still be provided.

Amalgam cuspal overlays are possible but again demand more occlusal space and thus reduction but without the adhesive benefit; in an intact tooth with only an access cavity, this approach would be too destructive. In any case, use of amalgam will be restricted in the future by the Minimata convention[186,187]. Amalgam currently has some restrictions based on guidance from the Chief Dental Officer of England (Department of Health Gateway number: 07929 To: All NHS England dental contract holders).

If a full crown is deemed necessary, it is likely that there will be sufficient tooth structure to require no additional form of reinforcement but this may depend on the size of the tooth and the volume of remaining dentine. Maxillary first premolars are typically those at risk from full crown preparations.

Teeth with class 2 plus access cavity

Loss of proximal tooth structure through management of class 2 caries lesions, in addition to the access cavity in posterior teeth, poses a mechanically different problem for protection of the tooth, as it becomes more susceptible to fracture[67]. Breach of the intact peripheral circle of bracing enamel renders buccal and palatal cusps that behave like flexible beams, particularly when two proximal boxes are linked by an isthmus. The choice of restorative material, design and approach depends on judgment of the potential for cuspal deflection sufficient to cause fracture, which would in turn depend on the width and depth of the proximal boxes[78], coupled with the nature of occlusal loading. The use of enamel-bonded resin may provide a reprieve for upto 3 years but the fracture rates then increase, presumably because of adhesive failure over time[73].

A tooth with a narrow, shallow proximal box should be little different from that with only an access cavity and may be treated in like manner. A tooth with a moderately wide, shallow proximal box and no signs of severe occlusal loading, may also be sufficiently well served with a plastic restorative material, either composite[182,183] or amalgam. A comparison between composites and amalgams, though not restricted to root-treated teeth, showed better survival of composites in the overall population and low-risk group but amalgam showed higher survival in three-surface restorations in high-risk patients[188]. Another study found no difference between composites and amalgam but that the larger the restoration, the greater the likelihood for failure[24]. One review found lower survival rates for posterior composites with higher frequency of secondary caries, though there was no difference in fracture susceptibility[189].

A tooth with two proximal boxes, with wide isthmus, coupled with heavy occlusal loading (possibly with cracks) would more likely benefit from cuspal protection[67]. The use of adhesive techniques coupled with tooth-coloured materials may increase the resistance to fracture of such teeth but this depends on the clinical durability of such bonds, which remains the weak link[73]. The technique has been recommended as a temporary means of "reinforcing" a tooth after endodontic treatment but must be used with caution on large cavities. Composite shrinkage may cause cusp deformation and fracture[139]. Nevertheless, favourable survival rates have been reported for posterior composite restorations upto at least 5 years[22,188,190]. Failures rates did however vary depending on practice and operator[22,190], suggesting technique-sensitivity, as well as when restoring root-treated teeth[190].

The options for occlusal protection with amalgam or composites overlays discussed above, still apply, with decreasing concern about the relative sacrifice of occlusal tooth structure as the occlusal cavity surface area increases. A technique of masking the internal cavity surface with composite, coupled with amalgam overlays showed good survival of a small sample with class 2 cavities upto 3 years[181]. Amalgam overlays can have good survival upto 15 years[191,192], with failures occurring through tooth or restoration fracture or caries. Likewise, good survival rates have also been recorded upto 5 years for composite overlays[21]; the type of restoration in the opposing arch influencing the outcomes. Failures occur through marginal deterioration, fractures and caries.

The most conservative option for providing cuspal protection is the partial veneer metal onlay[30,193]. The design and execution of such restorations is technically more demanding, plus the short height of such restorations places stringent requirements on the parallelism of multiple prepared surfaces. Provided a sufficient wrap-around effect is achieved and the preparation is minimally tapered, satisfactory retention and resistance form may be obtained. Appropriate design can restrict the extent of metal show at the buccal cusp or it may be sandblasted to reduce shine. Partial veneer onlay designs are versatile and may be modified to suit the situation if additional tooth tissue is missing or alternatively a three-quarter crown may be deployed. Both poor tooth preparation or restoration construction will compromise occlusal protection and aesthetics.

Patients who prefer tooth-coloured restorative material composite (direct or indirect) or ceramic should be informed and consented about the greater tooth structure sacrifice required to provide adequate material strength[21,185].

A full crown is always the last option to consider as it is the most destructive of tooth structure[193], which in the aesthetic zone would be constructed of high-performance ceramic or metal with pressed ceramic[180]. However, before considering such a restoration, the amount of tooth tissue likely to be lost in providing space for the thickness of metal and/or ceramic should be anticipated and estimated[193]. The minimum thickness required is 1.00-1.3 mm, which may weaken the tooth further but perhaps be an acceptable risk to secure the aesthetic requirement. Whilst indirect restorations have been credited with yielding better survival rates for root-treated teeth than those restored with direct restorations [15], the contrary is also sometimes reported[194]. This may be attributed to dentists reserving crowns for the most compromised teeth, as well as variation in the skills and experience of the dentist.

The need to “reinforce” the remaining tooth structure with a post (often fibre-post) to distribute some of the occlusal load into the root and indeed, whether the tooth then requires a crown attracts varying advice and opinion[61,136,153,156]. The decisive factor should be the amount of remaining tooth structure after crown preparation is complete[193] but this is difficult to predict in advance, since post-placement occurs before crown preparation. In the future, 3D workflows will enable virtual tooth preparation to predict the likely remaining tooth structure dependent upon choice of preparation design.

In conclusion, the initial treatment costs and the risks of complications differ between the simpler direct restorative approaches compared to the indirect approach. In one modeling analysis, composite restorations were found to be cheaper but less effective than indirect restorations for root-treated teeth, however, over a longer-term, the initial cheaper costs may be out-weighed by the cost of follow-up treatment[27].

Extensively damaged teeth with occlusal, proximal plus cuspal loss

Root-treated teeth broken down to the extent that retention and resistance form for an indirect cast restoration is compromised may first require installation of a core to supplement these features for final restoration placement. Retention for such core material may be achieved using a number of retentive devices (grooves, slots, dentine pins, dowels) but they should be independent of the final restoration and not compromise the strength of the remaining dentine or the core. The depth and size of retentive devices depend on the physical properties of the core material. Most of the currently available plastic materials require reasonable bulk for adequate strength, which limits their clinical application. The use of dentine pins has declined in general and is not recommended in root-treated teeth because of the stresses and cracks they can induce. The availability of the pulp chamber and root canals provide adequate opportunities for retention.

The pulp space may be used for retention in a number of ways, employing greater or lesser corono-apical extents of the space. The most conservative has been the “Nayyar amalgam dowel core”, involving filling of the pulp chamber with amalgam. The original recommendation suggested extending amalgam into the coronal 3mm of the root canals but this is unnecessary and the core may be confined to the intact pulp chamber. The amalgam could also be extended coronally to act as the final capped-cusp restoration or prepared for placement of an indirect restoration. A functional amalgam core requires an intact pulp chamber wall circumferentially with adequate depth and wall-thickness. Premolars by virtue of their size are not as suitable for such cores.

Just as for anterior teeth, when the remaining coronal dentine is inadequate to support such a core, additional retention may be gained by placing a post(s) into one or more canals; the most naturally wide and straight in the coronal part is preferred (palatal canal in maxillary molars and distal canals in mandibular molars). The post and the residual coronal dentine thus provide the collective retention and resistance form for the core. Multiple roots allow multiple posts to be placed, which if divergent (placed independently), do not have to comply with the rules of length stipulated for single-rooted teeth. Such posts can be very short but possess high strength and modulus of elasticity; that is, in the presence of minimal coronal tooth structure a metal alloy post is preferred. The coronal end of a post may weaken the core build-up and exert stress, depending on its size and shape, as well as the properties of the material.

Core materials

Cores fabricated from plastic materials (amalgam, composite, GIC) may serve as interim restorations before being prepared for cast restorations. The margins of the final indirect restoration must always be placed on sound tooth tissue, not the core material and indeed adherence to this principle will draw attention to the predictable restorability of the tooth.

Amalgam has been the material of choice for plastic cores because of its strength, versatility, and dimensional stability but the Minimata convention will draw this chapter to a close.

Composite cores have gained popularity because of their command-set and relative strength but they are not an equivalent replacement for amalgam. Its modulus of elasticity should be equal to or higher than that of dentine. In anterior teeth it has aesthetic advantage when used in combination with all-ceramic reconstructions. A disadvantage of composite cores is their tendency to absorb moisture and expand volumetrically; eugenol-based temporary cements may also soften the core and the moisture absorbed by the core could affect the physical properties of the permanent luting cement if it is acid-based (zinc phosphate, glass ionomer, polycarboxylate). Nevertheless, a five-year follow-up study on various types of cores found that as long as there was sufficient remaining height of dentine, there was no significant difference in survival of cast post-core, direct post and composite core or composite core without a post[195].

Resin-modified glass ionomer cements and compomers do not possess the same fracture strength as composites[196], and they also may undergo slow expansion with water absorption leading to cracks in overlying ceramic crowns[197]. Thus, they may exert stress on restorations and tooth structure. Cermets or metal-reinforced glass ionomers also do not possess sufficient strength to be placed in stress-bearing areas[198] and may only be considered as space-fillers to reduce the bulk of the cast restoration. They should not be used as a structural core providing the principal retention and resistance form and have declined in use and availability.

Cast cores with multiple posts may be used in multi-rooted teeth with little remaining coronal tooth structure by constructing only one of the posts integral with the core and cementing the remaining post(s) into their respective canals through the core. This method can be applied using either indirect or direct techniques. The canal providing the path of least resistance is selected for the principal post to help preserve tooth tissue. If a substantial amount of coronal tooth tissue needs to be sacrificed to provide a path of insertion for the core, it may be better to cement preformed posts into the canals and build up a core with plastic restorative materials.

The Endo-Crown

Going against all the principles established above, a new concept has emerged for restoration of severely destroyed root-treated teeth that possess supragingival margins and an intact pulp chamber. The notion is to use the pulp chamber to retain a monolithic composite or ceramic crown with a “dowel” extension into the pulp chamber. A variety of designs with different amounts of coronal tooth structure have been posited and tested[199-201]. It is suggested that the higher the modulus of elasticity of the restorative material, the more the stresses can be concentrated in the restorative material rather than in the cement interface or tooth structure[201]. Extension of posts into the roots achieved higher stresses in the adhesive cement-dentine interface [199].

Although the clinical data are limited, a systematic review suggested a success rate of 94-100%[202]. A 10-year retrospective study following 99 restorations, of which 57% were in molars and 76% were classified as class 3 (most of the coronal tooth structure missing), a survival rate of over 99% and success rate of 90% were achieved. It was suggested that this was even in the presence of occlusal risk factors such as bruxism or unfavourable occlusal relationships. The majority of restorations were made of lithium disilicate glass ceramic. The technique of bonding involved immediate dentine sealing, a three-step-etch and rinse bonding agent polymerized onto the dentine. The restorations were bonded with a specific technique and series of agents[203]. Further longer trials are needed to consolidate this data on what may be a promising technique for heavily compromised teeth.

Root-treated teeth as abutments

There may be a greater tendency for root-treated abutment teeth and their restorations to fail mechanically than vital abutments[95]. For this reason many operators avoid using root-treated teeth as abutments but it is also documented that such teeth *can* survive as bridge abutments[128]. The potential for failure is a function not only of endodontic status but also of the amount of remaining dentine, restoration design and occlusal loading. In one prospective trial of root-treated teeth restored with single crowns or as bridge abutments, teeth with 50% or more remaining tooth structure restored with a crown had a 90% survival rate over 84 months, compared to those with 50% or less tooth structure restored as bridge abutments, which had a survival rate of 57%[129]. Different bridge and denture designs impose different stresses on teeth and it is important to select a design likely to reduce such stresses. Fixed–fixed bridge designs distribute stresses equally between abutments, whereas, the minor retainer in a fixed–movable design takes the lower load. It is suggested that a combination of effective decision-making, attention to detail and high quality execution of procedures may nevertheless yield few complications, regardless of involvement of teeth in single crowns or bridges of different designs[64].

The terminal abutment for a free-end saddle design is likely to take greater loads than an abutment for a bounded saddle. Crown to root ratios, bracing, type of retention and rest seat design all influence lateral loading of abutment teeth. The number of remaining teeth and potential for bracing from other teeth and soft tissues may also dictate overall loading. The bridge or denture design selected should attempt to minimize stresses on root-treated teeth. Ng *et al*. (2011a)[56] observed that teeth functioning as prosthetic abutments had poorer survival. If possible, root-treated teeth should be avoided as abutments for prostheses or in provision of occlusal guidance in excursive movements.

Restoration of teeth with root canal retreatment

It has been questioned whether root canal retreatment may further weaken teeth and compromise restorability or its predictable restoration. However, Ng et al (2011a)[56] emphatically found the 4-year tooth survival following primary or secondary root canal treatment to be 95%, with thirteen prognostic factors common to both. A systematic review of laboratory studies evaluating the mechanical strength of root canal treated *versus* retreated teeth found little evidence to support a difference[204]. Nevertheless, it has been suggested that endodontic retreatment may influence the choice of definitive restoration of the tooth by the dentist[205].

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Value of root-filled teeth in maintaining a functional dentition for life

K Gulabivala & Y-L Ng

Table 1 – Prevalence of cusp fracture in root-treated teeth

Study	Number of teeth	Tooth type	Restoration type	Duration after treatment	Prevalence of cusp fracture
Akerboom et al. (1993)[72]	1415	Non-RF / RF	Amalgam (MO/DO)	10	1.8%
Hansen et al. (1990)[67]	1639	Posterior	Amalgam (MOD) Amalgam (MO/DO)	20	62% 26%
Hansen (1988)[73]	181 40	Premolars	Amalgam (MOD) Composite (MOD)	10	55% 20%
Hansen & Amussen (1990)[69]	332	Posterior	Composite (MOD) Composite (MO/DO)	10	8% 13%
Van Nieuwenhuysen et al. (2003)[74]	926	Posterior (60% RF)	Amalgam (partial) Composite (partial) Crown	Upto 16	9% 7% 0%
Dammaschke et al. (2013)[75]	676	Posterior	Various types	10	14% (0% – 37%)

Table 2 – Prevalence of vertical root fracture

Study	Number of teeth	Tooth type	Restoration type	Duration after treatment	Prevalence of vertical fracture
Morfis (1990)[76]	460	Single & multi-rooted	Full veneer crown ± post	>3	4%
Hansen et al. (1990)[67]	1639	Posterior	Amalgam (MOD) Amalgam (MO/DO)	20	4%
Van Nieuwenhuysen et al. (2003)[74]	926	Posterior (60% root treated)	Amalgam (complete) Composite (complete) Crown	Upto 16	4% 1% 3%
Ferrari et al. (2012)[61]	 104 31 35	Premolar	Full veneer crown with • 1-4 walls without post • Ferrule (+post) • No ferrule (+post)	6	 0% – 19% 22% (0%) 37% (11%)

Table 3 – Review studies and their findings on performance of posts in root-treated teeth

Review	Studies identified	Studies selected	Analysis	Key findings related the use of post
Heydecke & Peters 2002[143]	1,773	10 in vitro; 6 in vivo	Cast vs Direct post-cores	Survival of cast post-cores 88%; 86% for direct cores
Bolla et al 2008[144]	16,944	2 RCTs with 317 patients	Metal vs non-metal posts	Risk of failure greater with metal-cast posts (9/98) vs carbon-fibre posts (0/97); but high bias-risk
Theodosopoulou & Chochlidakis 2008[145]	1,163	6 RCTs, 2 CCTs, 2 CSs	Series of comparisons	Carbon fibre > cast alloy; Tapered cast alloy > Parapost; Parapost prefab > Parapost cast; Glass fibre > metal screw; Titanium > Glass fibre; Cast gold > carbon fibre
Faria et al 2011[29]	207	43 studies	By a series of factors	Root-treated tooth characteristics; tooth type; remaining tooth structure; cuspal coverage; use of posts
Soares et al 2012[142]	436	22 studies	Endo/perio failure, root fracture, tooth loss, post or restoration loss, caries	Ferrule indicated for fiber posts; Fiber post survival similar to cast metal posts; Metal posts survive well but fail irreversibly, unlike fiber posts
Barfeie et al 2015[146]	-	19 studies	Cause of failure of fibre posts	Adhesive failure in 16/19 trials; survival of fibre posts similar to metal posts in the short term
Figueiredo et al 2015[147]	248	14 studies: 7 RCTs and 7 cohort	Survival rate and failure type	Pooled survival 90% for metal posts; 84% for fibre posts; rate of catastrophic fractures similar for post-types; prefabricated metal and carbon fibre posts had 2× higher incidence of root fracture compared to cast metal and glass fibre
Sorrentino et al 2016[148]	4230	4 studies	Complications of fibre posts	Fibre post debonding; loss of retention; marginal gaps; fractures less frequent
Sarkis-Onofre et al 2017[141]	638	9 studies in qualitative analysis	Success/survival of post-retained restorations	Teeth without ferrule presented highest variation; teeth with remaining walls (1,2,3) presented lower variation; success/survival of posts with high elastic modulus 72-100%; posts with low elastic modulus 29-100%
Marchionatti et al 2017[149]	341	11 studies	Survival & failure mode of posts	Most studies show good survival; Fibre posts – 71-100%; Metal posts – 50-97%; no difference between various metal posts; remaining dentine height & ferrule increased longevity; Fibre posts fail by loss of retention, while metal posts fail by root fracture/post fracture/loss of retention; metal and fibre similar in short to medium term
Carvalho et al 2018[30]	-	-	Series of comparisons	Review preservation of coronal structure; partial vs full crown; ferrule; adhesive; no post; endocrowns
Wang et al 2019[150]	1,511	14 studies; 4 RCTs	Survival of fibre vs metal posts in severely damaged teeth	Fibre posts presented higher survival rates than metal posts but no differences were evident in success rates, post debonding or root fracture rates

Table 4 Clinical studies (Cohort or RCTs) evaluating survival of posts, restorations and root-treated anterior teeth (incisor, canine, premolar)

Study (type)	Post type	Sample size	Follow-up duration	Survival % (successful %)	Failure type	Predictors of success
Cagidiaco *et al.* 2008[152] (Randomised trial)	Prefabricated or customized fibre	60 premolars (345 patients)	3 yrs	77% Prefab 91% Custom 77%		Ferrule; No. of walls
Mannocci et al 2009[153] (Randomised trial)	Glass-fibre post plus ceramo-metal Crown; Composite build-up	117 premolars (117 patients)	3 yrs	Composite & crown 95% Composite 90%	LoR 38%; Marginal gap 62%	None identified
Bitter et al 2009[136] (Randomised trial)	Glass-fibre posts	120 teeth (90 patients)	32 mos	No post 90% Posts 93%	RF 44%; LoR 38%; PF 6%; Caries 6%; Substance loss 6%	No. of wall; Use of post if no wall
Ferrari et al 2012[61] (Randomised trial)	Glass-fibre posts (No post; prefab post; custom post); All crowned	360 premolars (345 patients)	6 yrs	No walls with post Ferrule 100%, No ferrule 94% No walls without post Ferrule 78%, No ferrule 65%	Crown dislodged 34-51%; Post debonded 0-48%; PF 20-39%; RF 4-25%; Endodontic failure 24-26%	No. of walls; Ferrule; Use of post if ≤2 walls; Prefab > customized posts
King et al 2003[154] (Prospective cohort)	Carbon fibre reinforced carbon endodontic post; Prefabricated wrought precious alloy post	27 maxillary single-rooted anterior teeth (18 patients); 16 CRFC posts with composite luting cement; 11 conventional posts cemented with zinc phosphate cement	Upto 87 mos	81%	LoR in CRFC 80%; Conventional PF (denture abutment) 20%	
Naumann et al 2005[155] (Prospective cohort)	Glass-fibre reinforced	149 posts (122 patients)	5-56 mos	69% AFR 6.7%	PF 45% LoR 29% Core failure 10% RF 10% Endodontic failure 6%	Tooth type; Restoration type; Proximal contact
Naumann et al 2012[156] (Prospective cohort)	Glass-fibre reinforced	149 posts (122 patients)	10 yrs	63% AFR 4.6%	PF 31%; LoR 31% Endodontic failure 13%	Tooth type; No. of walls
Kramer et al 2018[157] (Prospective cohort)	Titanium; Glass-fibre	195 posts (195 patients) (incisors, canines, premolars)	6 yrs	78% (72%); AFR 8.6%	PF 33%; Tooth fracture 26%	Post type (glass fibre worse); re-cementation 8× worse;

						age; sex;
Munaga et al 2018[158] (Prospective cohort)	Indirect cast-post; Direct composite post	128 teeth (82 patients)	3 yrs	Overall 91%	RF 2.3%; Radiolucency 7%;	None identified
Wierichs et al 2018[138] (Prospective cohort)	Composite build-ups without posts	192 teeth (192 patients)	10 yrs	94% (87%); AFR 2.4%		None identified
Sorensen & Martinoff 1984[128] (Retrospective cohort)	Cast P&Cs; Prefabricated and threaded posts; No posts; With or without coronal coverage	1272 teeth (6000 records)	1-25 yrs	Anterior teeth No post 87% Post 92% Crown 89% No crown 88% Posterior teeth No post 91% Post 93% Crown 96% No crown 56%		Coronal coverage improved longevity of premolars and molars
Jung et al 2007[159] (Retrospective cohort)	Cast gold P&C; Composite post build-up	41 cast P&Cs; 31 composite cores	5-10 yrs	Cast P&C 90% Composite cores 94%	Radiolucency 32% Probing depths 29% Caries 14% RF 7% LoR 7%	
Gomez-Polo et al 2010[160] (Retrospective cohort)	Prefabricated (variety); Cast cobalt-chrome	112 posts (85 patients)	10 yrs	Prefab 85% Cast 83%	LoR: cast 23% / prefab 12%; RF cast 12% / prefab 15%	
Bateli et al 2014[161] (Retrospective cohort)	Zirconia	64 posts (45 patients)	10 yrs	81%	Extractions/ Radiolucency	
Caserio Valea & Alonso De La Pena 2017[162] (Retrospective cohort)	Titanium and bonded amalgam	88 posts (66 patients)	18-22 yrs	90% (5 yrs) 64% (18 yrs) 48% (22 yrs)	LoR 24%; Caries 24%; RF 21%; Marginal leakage 14%	2mm+ ferrule; Tooth type (premolars worse)
Yee et al 2018[125] (Retrospective cohort)	Insurance claims data on P&C, crown treatment of root-filed teeth	160,040 RCTs		99% (1 yr) 96% (3 yrs) 92% (5 yrs) 84% (10 yrs)	Retreatment, apicectomy, extraction	P&C placed more ≤ 60 d after RCT; Crown ≤ 60 d after P&C; RCT performed by Endodontists

AFR = annual failure rate; LoR = loss of retention; RF = Root fracture; PF = post fracture; P&C = post-core; RCT = root canal treatment

Table 5 Studies on survival of posterior root-treated teeth with or without coronal coverage

Study (type)	With/without Coronal coverage; plus or minus posts	Sample size	Follow-up duration	Survival %	Failure type	Predictors of success
Sorensen & Martinoff 1984[128] (Retrospective cohort)	With or without coronal coverage; plus with or without posts	1273 teeth (6000 records)	1-25 yrs	Crown 96% No crown 56%	Dislodgment, TF; RF; (Iatrogenic root perforation).	Coronal coverage
Hansen et al 1990[67] (Retrospective cohort)	Premolars restored with amalgam without cuspal overlay (MO/DO/MOD)	1639 teeth	20 yrs	Teeth with MOD cavities: 72% (3 yrs) 43% (10 yrs) 37% (20 yrs)	Fracture mode: Lingual 63% Facial 25% Total 8% Vertical 4%	Amalgam with cuspal coverage; (Maxillary premolars, lingual cusp fracture was more prevalent; teeth in posterior location or lingual cusp fracture results in more serious failures i.e. extraction)
Hansen & Asmussen 1990[69] (Retrospective cohort)	Premolars restored with composite without cuspal overlay (MO/DO/MOD)	190 teeth	Upto 10 yrs	13% (10 yrs)	No information	Chemically cured composite; intermediate layer of low-viscosity resin
Hansen & Asmussen 1993[68] (Retrospective cohort)	Premolars/molars restored with composite or amalgam without cuspal overlay (MO/DO/MOD)	1584 teeth	Teeth restored before 1975 or after 1979	51-94% (3 yrs) 36-90% (7 yrs) 36-78% (20 yrs)	Sub or supra-crestal cusp fractures; after 1979, sub-crestal 2× as high as before 1975	Teeth restored before 1975 had lower frequency of cusp fracture than after 1979 (*Explained by the introduction of high copper amalgam & Gates Glidden burs to achieve straight-line access*)
Mannocci et al 2009[153] (Randomised trial)	Premolars restored with ceramometal crown vs composite build-up plus glass-fibre post	117 teeth (117 patients)	3 yrs	Composite & crown 95% Composite 90%	LoR 38%; Marginal gap 62%	None identified
Ferrari et al 2012[61] (Randomised trial)	Premolars restored with glass-fibre posts (No post; prefab post; custom post); All crowned	360 teeth (345 patients)	6 yrs	<u>No walls with post</u> Ferrule 100%, No ferrule 94% <u>No walls without post</u> Ferrule 78%, No ferrule 65%	Crown dislodged 34-51%; Post debonded 0-48%; PF 20-39%; RF 4-25%; Endodontic failure 24-26%	No. of walls; Ferrule; Use of post if ≤2 walls; Prefab > customized posts
Monaco et al 2017[180] (Randomised trial)	Premolars/molars restored with Zirconia-based vs metal-based crowns with over-pressed ceramic on	90 teeth (72 patients)	5 yrs	Restoration: Survival 97-98% Success 91-92%	Chipping of ceramic in both materials; Core fracture; PFM crown lost due to a RF.	No difference between crown types
Shafiei et al 2010[181] (Prospective cohort)	Maxillary premolars restored with cuspal coverage with combined composite-amalgam	36 teeth (36 patients)	3 yrs	None fractured	All except 2 received alpha scores; 4 restorations with slight discolouration	

Dias et al 2018[21] (Prospective cohort)	Premolar/molars restored with cuspal coverage composite	150 teeth (150 patients)	Upto 5 yrs	Tooth: 100%; Restoration: Success 96%	Marginal discolouration; filling fractures; caries	Type of restorative material or tooth in opposing arch
Aquilino & Caplan 2002[15] (Retrospective cohort)	Incisors/premolars/ molars with or without crowns	203 teeth (156 patients)	Upto 10 yr	79%	No information	Crowning; 2 proximal contacts; Absence of caries at access; Not a 2nd molar
Dammaschke et al 2003[75] (Retrospective cohort)	RCT by students on incisors, premolars and molars	190 teeth (144 patients)	10 yrs	85%	Extraction	Pre-operative periapical radiolucency; RF within apical 2mm; Post-crowned teeth
Nagasiri & Chitmongkolsuk 2005[60] (Retrospective cohort)	Molars restored with composite or amalgam without crowns	220 teeth (203 patients)	Upto 5 yrs	Tooth: 94%; Restoration: 96% (1 yr); 88% (2 yrs); 36% (5 yrs) *(78% for teeth with maximum tooth structure)*	Caries; Crack line; Lost/fracture of restoration; TF; Vertical RF; *(Endodontic failure excluded)*	Composite filled teeth; Amount of tooth structure
Fokkinga et al 2008[182] (Retrospective cohort)	Composite resin core-crowns (Class 2 cavities with cusp replacement) with or without prefabricated posts (anterior, premolar, molar)	98 teeth (87 patients)	Upto 17 yrs	Tooth: 79%; Restoration: 53%	Caries; Crowns; Extractions	Posts had no influence
Pratt et al 2016[124] (Retrospective cohort)	Teeth receiving crowns before or after 4 mos following RCT	882 teeth (880 patients)	8 yrs	88%	Crown fractures 60%; Restoration failure 20%; Vertical RF 8%; Unknown 12%	Crowned within 4 mos after RCT
Suksaphar et al 2018[183] (Retrospective cohort)	Premolars restored with crowns or direct composites	122 teeth (122 patients)	Upto 5 yrs	Restoration: 86%; (Resin composite 77%; Full-coverage crowns 95%)	Higher incidence of restorability after fracture in composite-restored teeth	Crowning; Teeth with ≤2 tooth surface losses & 2 proximal contacts restored with composite survived as well as those crowned

RCT = root canal treatment; LoR = loss of retention; RF = Root fracture; PF = post fracture, P&C = post-core; TF = tooth fracture