Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature, Part II (Evaluation of fatigue behavior, interfaces, and in vivo studies)

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Objective: The restoration of endodontically treated teeth has long been guided by empirical rather than biomechanical concepts. Part I of this literature review presented up-to-date knowledge about changes in tissue structure and properties following endodontic therapy, as well as the behavior of restored teeth in monotonic mechanical tests or finite element analysis. The aim of the second part is to review current knowledge about the various interfaces of restored, nonvital teeth and their behavior in fatigue and clinical studies. **Review method:** The basic search process included a systematic review of articles contained in the PubMed/Medline database, dating between 1990 and 2005, using single or combined key words to obtain the most comprehensive list of references; a perusal of the references of the references completed the review. **Relevant information and conclusions:** Nonvital teeth restored with composite resin or composite resin combined with fiber posts resisted fatigue tests and currently represent the best treatment option. In comparison to rigid metal and/or ceramic posts, when composite resin or composite resin/fiber posts fail, the occurrence of interfacial defects or severe tooth breakdown is less likely. Adhesion into the root, however, remains a challenge because of the unfavorable ovoid canal configuration, as well as critical dentin microstructure in the deepest parts of the canal. Thus, specific combinations of adhesives and cements are recommended. The clinical performance of post-and-core restorations proved satisfactory overall, in particular with a contemporary restorative approach using composite resin and fiber posts. However, the clinical literature does not clearly isolate or identify exact parameters critical to success. This, in turn, emphasizes the importance and relevance of in vitro studies to further improve the quality and long-term stability of prosthetic foundations. *(Quintessence Int 2008;39:117–129)*

Key words: clinical studies, fatigue, nonvital teeth, posts and cores, root adhesion

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The restoration of endodontically treated teeth has long been a controversial topic, often approached empirically and based on assumptions rather than scientific evidence. The first part of this literature review presented current knowledge about changes in tissue structure and properties following endodontic therapy and the behavior of restored teeth in monotonic mechanical tests or finite element analysis.

The loss of tooth vitality is not accompanied by significant change in tissue moisture or collagen structure,[1–3] while endodontic therapy, and, in particular, the use of irrigants such as sodium hypochlorite and chelators, proved to soften dentin.[4–9] Only minor differences in dentin microhardness or hardness were reported between vital and nonvital dentin[10,11]; larger differences, however, can exist, but they have to be attributed to root location (vertically or transversally)[12–14] and dentin microstructure (peritubular or intertubular).[15,16]

The most important changes in tooth biomechanics is attributed to the loss of tissue either at radicular[17,18] or coronal[18–21] levels, which points out the importance of a highly conservative approach during endodontic and restorative procedures. The significance of remaining cervical tissue, known as the ferrule effect, was also well-documented.[22,23] The restorative approach can also influence the stability of nonvital teeth; with nonadhesive techniques, a full occlusal coverage restoration[24,25] was suggested to protect the remaining structure. In general, the use of composite resin in conjunction with less rigid fiber posts appeared to be the most effective technique for the restoration of severely decayed nonvital teeth, in consideration of still-perfectible adhesive procedures[26–28]; the latter option had a better protective effect against root fractures.

During the simulation of perfect cohesive interfaces (with finite element analysis), rigid posts showed a potential to lower stresses in the critical cervical area.[29] In general, rigid ceramic or metal posts tend to distribute stresses internally or transfer them more apically (leading possibly to more disastrous failures), while softer fiber posts with composite resin tend to concentrate stresses along the adhesive interface but also transfer them more uniformly throughout the tooth and surrounding tissues.[26,30]

The aforementioned information and conclusions are not complete, however, as they do not take into consideration other specific strains of the oral cavity, in particular, cyclic forces (known as fatigue), which likely account for the majority of clinical failures.[31,32]

The aim of part II of this review is to focus on the biomechanical behavior of endodontically treated teeth following fatigue tests and subsequent influence of the numerous restoration interfaces involved. Then, a review of available relevant clinical studies should serve to determine the performance of restored nonvital teeth and eventually which type of foundation is the most stable in the long term. Based on available conclusions of in vitro and in vivo studies covered in parts I and II of this review, clinical recommendations for the restoration of pulpless teeth will be presented.

REVIEW METHOD

The search strategy included a review of the PubMed/Medline database for dental journals with use of the following primary key words/phrases: nonvital tooth/teeth, endodontically treated tooth/teeth, posts and cores, foundation restoration, endocrowns, and radicular dentin. These basic key words were used alone or combined with secondary key words such as clinical study, clinical trial, finite element analysis, literature review, resistance to fracture, adhesion, cyclic loading, and fatigue. The systematic review covered articles published between 1990 and 2005. Perusal of the references of relevant papers rounded out the review. A few older and basic references were extracted from the authors' literature database and purposefully included in this review. Studies were classified and analyzed according to the parameters or hypothesis investigated:

- Physicochemical composition of tissues
- Tissue microhardness and hardness
- Fracture resistance following preparation and restoration, resistance to post-and-core dislodgment (mechanical tests)
- Stress simulation using photoelasticity, finite-element analysis, or fatigue devices reproducing masticatory forces and other buccal strains
- Evaluation of restoration adaptation and interfaces, including bond strength tests
- Clinical studies

The literature dealing with the first 3 parameters, photoelasticity, and finite element analysis was summarized in part I of this review.[33]

FATIGUE TESTING OF RESTORED NONVITAL TEETH

Fatigue studies mimic the effect of repeated mechanical and thermal cycles, as well as the influence of a humid oral environment.[34,35] In the case of vital tooth simulation, even the effect of pulpal pressure can be reproduced.[36,37] This is the most sophisticated in vitro tool when reproducing clinical reality. Its chief advantage over clinical studies is the reduction of the number of uncontrolled variables. Also, it enables the testing of samples with well-defined biomechanical status. The first devices specifically developed to reproduce masticatory strains and thermocycling, and even some chemical and abrasion phenomenon were used to evaluate the behavior of class II restorations.[34–38]

A study exploring the fracture resistance after thermal and mechanical cycling of teeth restored with posts and cores and full-coverage crowns showed a better performance by fiber-reinforced, composite resin posts and cores.[39] Dietschi et al[40] demonstrated that composite resin cores with metal, fiber, or ceramic posts exhibit variable proportions of interfacial defects, following cyclic loading with physiological forces; the more rigid ceramic and metal posts showed the highest proportion of gaps at the dentin-post or dentin-core interface. Mannocci et al[41] also tested fiber and zirconium oxide posts in conjunction with composite resin cores and restored with Empress crowns (Ivoclar Vivadent) and evaluated their fatigue behavior under higher (nonphysiological) forces. They concluded that the use of rigid post material, such as zirconium oxide, will result in higher failure rates, mainly in the form of root fractures. Such dramatic failures are clinically untreatable.

The placement of a post in a nonvital incisor with 2 proximal restorations does not bring additional resistance to fracture[42]; in fact, fewer catastrophic failures (clinically treatable) were reported with teeth restored without posts. Likewise, it seems that the increased tooth fragility produced by the canal preparation prior to post insertion is not fully compensated for by the luting composite resin. In another fatigue study on restored maxillary central incisors, a 100% survival rate was found for teeth with access cavities closed with only composite resin. On the contrary, a 10% to 40% failure rate was recorded for teeth restored with experimental composite resin post-and-ceramic cores and 1-piece zirconium oxide or cast gold posts and cores.[43] The use of titanium posts cemented with zinc phosphate presented more leakage after fatigue compared to adhesively luted ceramic or fiber posts underneath composite resin cores.[44]

Cast dowel cores covered by crowns of different ferrule heights were tested under cyclic load until failure; the results showed that 0.5- and 1.0-mm ferrule heights led to earlier failure than 1.5- and 2.0-mm ferrule heights.[45]

Most of the aforementioned studies pointed out that different interfaces of post-and-core restorations are imperfect from a quality standpoint. Such imperfections are especially notable at the adhesive interface to radicular dentin. Tissue conservation, as well as the use of materials with physical properties that closely match natural tissues, appear to be the most suitable choices.[46] Likewise, placement of a post should not be categorically considered for endodontically treated teeth.

RESTORATION ADAPTATION AND QUALITY OF INTERFACES

Micromorphology of the adhesive interface

A well-structured resin-dentin interdiffusion zone was observed at the interface with radicular dentin using either total-etch or self-etch adhesives; however, this hybrid layer was more uniform when a total-etch system was used.[41] Ferrari et al[47] evaluated the structural characteristics of resin-radicular dentin interfaces and concluded that the hybrid layer thickness and resin tag density diminished from the coronal to the apical third of a root. In vivo confocal and SEM (scanning electron microscope) microscopy[48] demonstrated that the penetration of adhesives inside radicular dentin proved to be complete in only one-third of extracted teeth in the apical third and in two-thirds of the samples in the middle and coronal thirds. The same authors evaluated the micromorphology of failed adhesive interfaces and found that the failure always occurred between either the hybrid layer and bonding resin or the bonding resin and composite resin cement, with higher proportions of interfacial defects at the hybrid layer after long periods of clinical service. These findings demonstrate the limited stability of the hybrid-layer interface. The limited penetration of the adhesive in the apical third of the root is likely related to the reduced number of tubules in the root apical region of elderly teeth.[49,50] The reduced microtensile bond strength of some resin cements observed in the apical portion of the root confirms these findings.[51] Another in vitro study[46] confirmed the higher occurrence of debonding at the top of the hybrid layer, with either SEM or confocal microscopy. It was also shown that the adhesive interface demonstrates a well-organized structure with hybrid layer and resin-tag formation where good adhesion is present, whereas a poorly structured interface is visible in most debonded areas.[46]

Bond strength and adhesive interface with pulpal-floor and radicular dentin

Adhesion to pulpal-floor dentin measured by microtensile bond strength test proved to be inferior to adhesion to coronal dentin with either a prime-and-bond system (15.6 versus 29.9 MPa) or 2-step self-etch adhesive (22.5 versus 36.0 MPa).[52] Lopes et al[53] have also shown that adhesion to pulpal chamber dentin was more reliable than to root-canal dentin. These findings might be explained by the difference in the collagen cross-linking structure at the different dentin locations.[54]

Comparisons between microtensile bond strength of different luting systems to flat root dentin specimens (favorable C-factor) or ovoid canal specimens (unfavorable C-factor) have confirmed the influence of substrate configuration (C-factor) and adhesive luting system[51]; bond strength was lowered in a full canal with dual-cured cements, while it remained unchanged with a mere chemical curing cement, possibly due to a slower polymerization process. Once again, a reduction of the bond strength was observed with increasing depth in the canal, with 2 of the cements tested. In another study, the type of composite resin cement-curing mode (dual- or self-cure) also proved to influence the bond strength of several adhesives to radicular dentin; the highest values were obtained for practically all adhesives tested when used with cement in a dual-cure mode.[52] The total-etch technique also appeared to produce higher bond strength values than the self-etching approach.[53] In fact, it was shown that self-etching primers should not be combined with chemical- or dual-cured cements, due to the remaining acidic components of the primer[56–59]; although those tests were performed on vital coronal dentin, such findings can also be relevant for the cementation of posts to radicular dentin.

Endodontic irrigants such as chloroform, halothane, hydrogen peroxide, and sodium hypochlorite (NaOCl) reduce bond strength to dentin, while chlorexidine did not affect adhesion.[60,61] However, according to Varela et al,[62] the influence of sodium hypochlorite treatment on dentin bond strength might vary with the adhesive used. In addition, the use of NaOCl proved to influence the resin tag morphology; with treatment, resin tags presented a cylindrical, solid shape instead of a hollow, tapered appearance.[62]

Bond strength values measured with a push-out test appeared to depend on the post type and root level, while sealer type or bonding agent had no influence.[63] Actually, bond strength values were superior at the coronal level and with fiber posts, compared to more apical radicular levels. Also, fiber posts provided better bond strength values than ceramic posts. When the tensile force required to dislodge a translucent fiber post cemented by either light-curing adhesive-cement system or dual-curing system was tested, the light-curing system resulted in slightly inferior bond strength values but provided a better adaptation than the dual-curing system.[64] When comparing them in a push-out test, the bond strength of fiber post to radicular dentin cemented with either a luting (unfilled or low filler content) or restorative composite resin, higher values were obtained with the restorative composite resins.[65] However, Goracci et al[66] have shown that push-out tests used to evaluate adhesion of fiber posts to dentin were more operator-dependent than microtensile bond strength tests.

Bond strength and interface between posts and luting/core composite resin

Following a pull-out test, adhesively cemented carbon-fiber posts presented bond strength values of 25 MPa between post and luting cement.[67] A finite element analysis of the same study configuration did also show that stresses accumulate at the post-cement interface and in the cement bulk itself, lowering stresses in radicular dentin due to the use of a post material of low elasticity modulus.[67] Boschian Pest et al[65] found similar adhesion values between fiber post and cement for unfilled, low-filled (luting), and highly filled (restorative) materials following a push-out test. In a pull-out test, sandblasting used to create microretentions lowered the bond strength between carbon posts and luting composite resin due to alumina particles impinging carbon fibers.[68] Quintas et al[69] found no difference in tensile bond strength between composite resin core and sandblasted or serrated carbon fiber posts. The use of serrated posts appears to be a more reliable approach to increase stability of the post inside the canal.

When testing the interface between composite resin cores and smooth fiber or serrated stainless steel posts, higher tensile strength values were obtained with the metal posts, due to the primary influence of macromechanical retention.[70] For adhesion between partially stabilized zirconium oxide posts and pressed glass ceramic or composite resin core materials, the use of tribochemical silicoating provided the best retention.[71]

CLINICAL STUDIES

The review of the rather abundant clinical literature on the long-term performance of prosthetic restorations confirms the diversity of restorative techniques and materials applied to vital and nonvital abutments and the absence of consensus or standardization of evaluation parameters for prosthetic restorations.[72,73]

When comparing the long-term clinical behavior of vital and nonvital teeth (18 to 23 years), Palmqvist and Scwartz[74] suggested that a higher failure risk was associated with endodontically treated teeth. Conversely, Valderhaug et al found no difference in the survival rate between vital and nonvital abutments over 5- to 25-year follow-ups, which confirms the inconclusiveness of many clinical studies.[75]

Over a 9- to 11-year follow-up of 400 restored nonvital teeth using various adhesive and nonadhesive restorative techniques, Aquilino and Caplan[76] found that teeth without prosthetic restorations had a failure rate 6 times higher than teeth with coronal coverage. In a similar study using an even more strict evaluation protocol, Mannocci et al[77] found no difference between the 3-year failure rate of 117 nonvital premolars restored with or without full-coverage coronal metal-ceramic crowns; this contrasting conclusion might be attributed to the strict use of adhesive techniques but also to the limited evaluation period.

Anterior teeth restored with cast post-and-core buildups surveyed over a 10-year period showed an 82% survival rate; in the failure group, recementation or rerestoration were needed in 46% and 32% of the cases, respectively.[78] In another 10-year study with only a limited number of cases (50 restorations surveyed), only 1 failure was reported within the 3 gold post-and-core systems, while 2 failures were reported in the group of prefabricated metal posts and composite resin cores, accounting for an overall 6% failure rate.[79] The authors also concluded that cast gold posts and cores are appropriate for the long-term reconstruction of nonvital teeth.

Mentink et al[80] evaluated 112 core buildups consisting of metal prefabricated posts with composite resin cores over an average period of 7.9 years and found a 12.5% failure rate, with almost half the teeth having to be extracted; the Dentatus post proved here to augment the risk of root fracture. In another study comparing the 4- to 5-year clinical

Fig 1 Do we always need a post? The existing literature suggests that posts are not needed when full coronal substances are present; the indication and placement of a ceramic post as seen here is questionable.

behavior of 788 nonvital teeth restored with different types of post and cores, parallel serrated metal posts with composite resin cores showed a lower failure rate (8%) than tapered cast gold posts and cores (15%)[81]; decementation proved to be the most common reason for failure. The clinical behavior of 286 root-filled teeth restored with 2 different prefabricated metal posts and cores was evaluated over a mean 2.3- or 3.9-year period; 18 restorations examined failed (6.3%) at the end of the evaluation period and required extraction.[82] The failure rate was correlated to the post position, length of the root canal filling, and insertion period. Actually, an eccentric post placement or placement with an intra-radicular length smaller than the crown height was correlated to higher failure rates.

A survey of 236 teeth restored with adhesive carbon fiber posts (Composipost, RTD) underneath metal-ceramic or ceramic full-coverage crowns (90% of the cases surveyed) or partial-coverage composite resin restorations, demonstrated a complete absence of failure during an average 32-month observation period.[83] The authors concluded that this new restorative option represents an interesting alternative to conventional metal-composite resin or cast-gold posts and cores. Ferrari et al[84] controlled 1,304 prosthetic restorations made on nonvital teeth previously restored with different adhesive posts and cores (carbon-and-quartz fiber posts) over a 1- to 6-year period and found an overall failure rate of 3.2%, which is considered a very satisfactory performance. When comparing the 4-year clinical behavior of cast posts and cores to fiber-reinforced, composite resin posts and cores, a 95% clinical success was obtained with the adhesive approach against only 84% for the metal restoration[85]; root fractures and crown dislodgments were observed only in the cast post-and-core group. However, the respective role of different influential factors such as tissue conservation, adhesion, and material properties to explain the good performance of the adhesive foundations cannot be ascertained. In a 30-month follow-up clinical trial of 180 endodontically treated teeth adhesively restored with quartz-fiber posts and full-coverage ceramic crowns, Malferrari et al[86] reported only 3 failures (1.7%) due to decementation of the post-and-core buildup during removal of the temporary crown; these teeth could, however, be retreated conservatively; no root or post-and-core fracture or crown decementation were reported during the subsequent 30-month observation period.

Endocrowns represent an interesting and conservative alternative to full-coverage crowns[87]; according to a 14- to 35.5-month follow-up period of 19 Cerec (Sirona) endocrowns, only one failure occurred.

Unlike the apparent conclusiveness of the aforementioned studies, a comprehensive overview of survival rates for nonvital teeth, with observation periods from 1 to 11 years and comparisons between restoration types or localizations, has shown no clear trend. In fact, annual failure rates of any given restorative technique fall within the same range (0.5% to 3%). However, it is highly illogical to assume that such dissimilar restorative materials and techniques show a similar clinical behavior. Considering the inherent variables of clinical studies, such as patient selection, group size, experience, and number of operators, it could be assumed that such variables tend to level the influence of restorative materials and techniques when observing large numbers of restorations or when combining results of clinical studies.

In an attempt to analyze the behavior of post-and-core restorations, Creugers et al[72] selected 16 studies presenting durability data

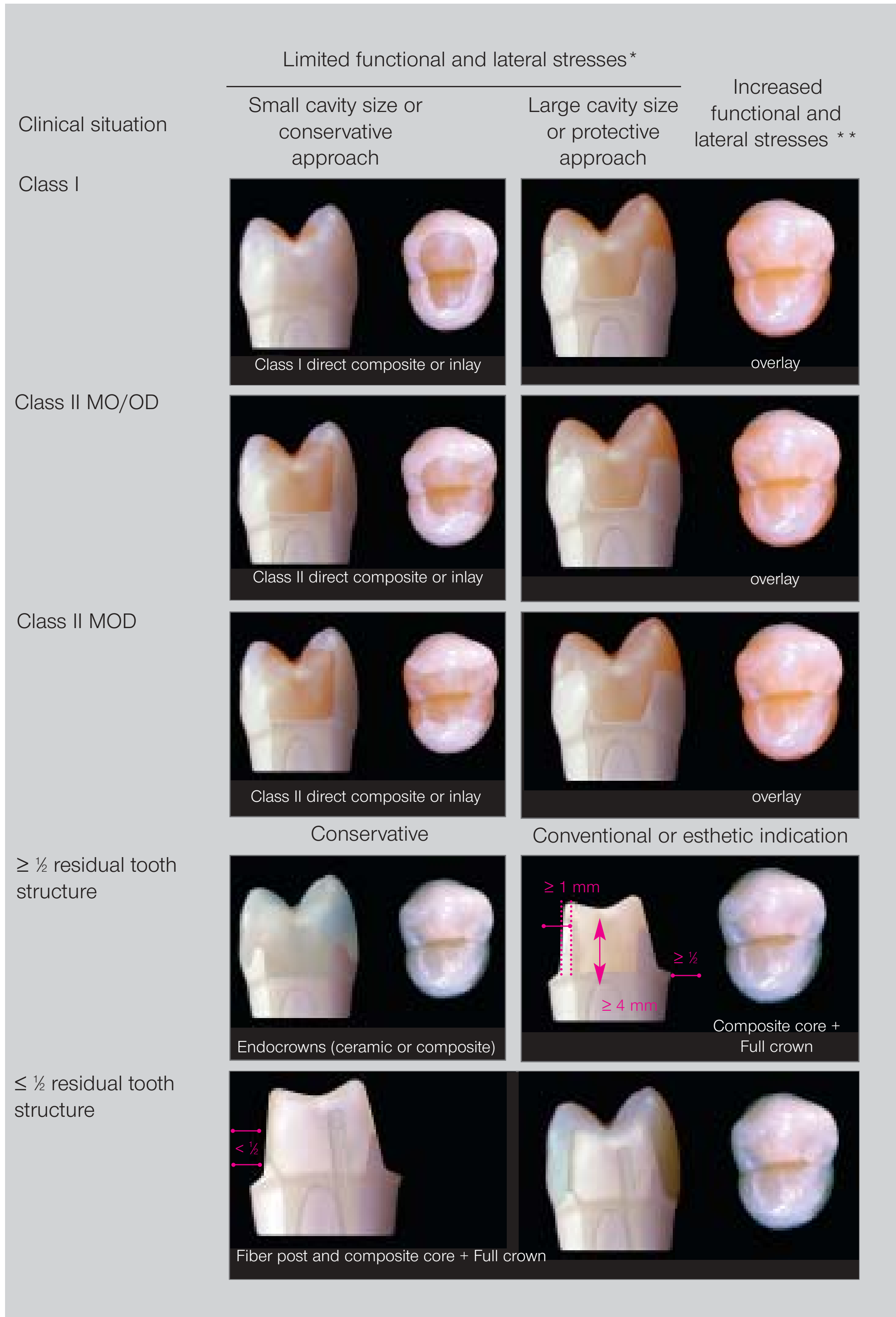
Fig 2 Can a tooth reinforce tooth structure? (*a*) Preoperative view of a root canal–treated maxillary central incisor, showing almost fully intact coronal structure. (*b*) Lingual view of the same tooth; the rationale was to maintain existing tooth structure and improve mechanical stability by post placement. (*c*) The ceramic post used did not, however, prevent a fracture of both tooth and post, requiring retreatment. Due to the significant coronal tooth structure lost, the tooth was finally restored with a cast post-and-core and full prosthetic restoration. With minimal residual tooth structure and absence of ferrule effect, newer options such as fiber-reinforced posts and cores did not prove of long-term clinical safety.

Fig 3 Typical configuration allowing a conservative treatment of a nonvital tooth using adhesive technique without reinforcement or retentive features of prosthetic foundation. (*a*) Preoperative view of the maxillary left central incisor, endodontically treated with large composite buildup; its unesthetic appearance and improper form requires retreatment. (*b*) Thickness and height of remaining tooth structure allow the placement of composite as prosthetic foundation without additional retentive structure. (*c*) Completed conservative composite buildup. (*d*) An all-ceramic crown finalizes the treatment.

Fig 4 Typical configuration allowing conservative treatment of an endodontically treated tooth using an adhesive technique with a post as an additional retentive feature. (*a*) Preoperative view: the maxillary right central incisor is nonvital with a large composite restoration. (*b* and *c*) After removal of existing restorative materials, the residual tooth structure is judged insufficient (width and height) to assume full retention and strength as a prosthetic foundation. (*d* and *e*) A white fiber post is used as a retentive feature. (*f* and *g*) Completed prosthetic treatment with all-ceramic restoration on the right central and veneer on the left central incisor.

but could only include 3 of them due to their exclusion criteria. With the same objective of presenting a survival analysis of in vivo studies on posts and cores, Heydecke and Peters[73] concluded that randomized clinical trials on this topic were not available, which points to the weakness of most clinical trial protocols and lack of standardized evaluation method. Actually, the relevance of clinical evaluations in this particular field could be appreciably improved by a case selection protocol, which would define the structural integrity of the tooth to be restored and the biomechanical parameters of the restoration (ie, tooth location, occlusal patterns, and type of rehabilitation); this is particularly important since it becomes almost impossible to analyze these parameters after the placement of the prosthetic restoration. Therefore, a significant effort should be made to plan longitudinal clinical trials, preferably in the form of multicenter studies, rather than just using data obtained from regular maintenance or recall appointments (retrospective studies), which often do not provide important information about pretreatment tooth biomechanical status; a specific evaluation index should also be created for this purpose. Presently, there is a clear lack of reports in this field having a high position in the hierarchy of evidences.[88-90]

Furthermore, clinicians must integrate some essential clinical elements in the equation which cannot be evaluated in vitro and even rarely taken into consideration in clinical trials (uncontrolled variables) on endodontically treated teeth; elements specific to each patient are caries risk, occlusion determinants (canine or group guidance, type of occlusion, overjet, and overbite), and the presence or absence of parafunctions which allow much more precise determination of biomechanical potential or risk of the intended restoration.



* Relatively flat anatomy and group guidance, normal function.
** Group guidance, steep occlusal anatomy, parafunctions.

Fig 5 Current recommendations for the treatment of nonvital teeth.

CONCLUSIONS

Due to the more precise control of biomechanical parameters and absence of uncontrolled variables inherent to clinical trials, fatigue studies can be regarded as the most pertinent source of information regarding the comparison of techniques and materials used for the restoration of endodontically treated teeth. Fatigue studies have clearly demonstrated the importance of tissue conservation and presence of a ferrule effect to optimize tooth biomechanical behavior; therefore, when enough tissue is present, a post is not needed (Figs 1 and 2). In the future, with a more meticulous application of contemporary conservative preparation and restoration techniques, post placement should become the exception rather than the rule (Fig 3). However, when a post is needed to increase stability of the foundation, resin-fiber posts with physical properties close to natural dentin, adhesively luted, appear to be the most suitable option (Figs 4 and 5).

Adhesion to the radicular dentin remains a clinical challenge due to the negative influence of endodontic irrigants and disinfectants, as well as the unfavorable canal configuration factor. Therefore, in order to establish the best possible adhesion within the root, only specific combinations of dentin adhesives and luting cements proved efficient; presently, total etch adhesives combined with a dual-curing cement appear to be the best choice. Due to the good adhesion with coronal tissues but reduced adhesion in the deeper canal portions, adhesively luted posts do not need to extend as deeply as posts conventionally cemented. In general, micromechanical retention or silicoating, respectively, proved useful to stabilize the interface with composite resin for metal and fiber posts or ceramic posts.

Clinical studies, which practically never provide the necessary information about initial tooth biomechanical status, nor do they adhere to strict research protocols, failed to bring meaningful information about the relative indication and performance of the numerous materials and techniques used to restore endodontically treated teeth. Overall, however, annual failure rates for conventional posts and cores and, in particular, contemporary adhesive fiber-composite resin foundations fail within acceptable to satisfactory ranges over relatively long observation periods, with clear influence of noncontrolled clinical variables.

Despite the fact that large quantities of evidence are still missing, it can be stated that the restoration of nonvital teeth has evolved from a completely empirical approach to biomechanically driven concepts, the conservation of tissue and adhesion being the most relevant elements for improved long-term success.

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