Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature—Part 1. Composition and micro- and macrostructure alterations

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The specific biomechanical alterations related to vitality loss or endodontic procedures are confusing issues for the practitioner and have been controversially approached from a clinical standpoint. The aim of part 1 of this literature review is to present an overview of the current knowledge about composition changes, structural alterations, and status following endodontic therapy and restorative procedures. The basic search process included a systematic review of the PubMed/Medline database 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 relevant sources completed the review. Only negligible alterations in tissue moisture and composition attributable to vitality loss or endodontic therapy were reported. Loss of vitality followed by proper endodontic therapy proved to affect tooth biomechanical behavior only to a limited extent. Conversely, tooth strength is reduced in proportion to coronal tissue loss, due to either caries lesion or restorative procedures. Therefore, the best current approach for restoring endodontically treated teeth seems to *(1)* minimize tissue sacrifice, especially in the cervical area so that a ferrule effect can be created, *(2)* use adhesive procedures at both radicular and coronal levels to strengthen remaining tooth structure and optimize restoration stability and retention, and *(3)* use post and core materials with physical properties close to those of natural dentin, because of the limitations of current adhesive procedures. *(Quintessence Int 2007;38:733–743)*

Key words: endodontic therapy, nonvital tooth, post and core, tooth biomechanics, tooth strength

Biomechanical failures of restored nonvital teeth today still are a critical issue in restorative and prosthetic dentistry.[1] Apart from mere endodontic or prosthodontic complications, such failures involve leakage, recurrent caries lesion, fissures, and fractures of the root. In such a situation, restoration replacement, at a minimum, or tooth extraction will be required. Practitioners' decisions regarding the selection of materials and restorative techniques are made difficult by the number of existing options; in fact, almost every dental material so far has been used for the restoration of endodontically treated teeth, employing either direct or indirect techniques. Moreover, the related literature points out the lack of accepted clinical standards and consensus regarding the optimal way of restoring nonvital teeth.[2,3] Actually, the multi-

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ple choices of evaluation methods lead to conflicting conclusions, mainly because investigation protocols usually explore only one aspect of the restoration behavior or are of poor methodological quality.[4] In this field, as in many others in dentistry, a systematic review of the existing literature is needed to help the practitioner make treatment decisions based on scientific evidence.[5,6]

The aim of the first part of this review is to emphasize the composition and structural alterations resulting from the loss of pulp vitality and from endodontic and various restorative procedures; the combined results and conclusions of the most relevant in vitro studies will lead to basic recommendations for material selection and treatment of pulpless teeth.

REVIEW METHOD

The search strategy included a review of the PubMed/Medline database for dental journals, with use of the following primary key words: nonvital tooth/teeth, endodontically treated tooth/teeth, pulpless tooth/teeth, posts and cores, foundation restoration, endocrowns, and radicular dentin. These basic key words were used alone or in combination with secondary key words: literature review, resistance to fracture, adhesion, cyclic loading, fatigue, and finite element analysis. The systematic review covered literature from 1990 to 2005. Perusal of the references of relevant papers (references of the references) completed the review. A few older, basic references were extracted from the authors' literature database and deliberately included in this review. Reports and conclusions of selected studies were classified and analyzed according to the parameters or hypothesis investigated:

- Dentin composition
- Dentin or restorative material physical characteristics
- Fracture resistance, tooth stiffness, and other monotonic mechanical tests
- Stress simulation using photoelastic studies and finite element analysis

BIOMECHANICAL CHANGES FOLLOWING LOSS OF PULP VITALITY OR ENDODONTIC THERAPY

The changes in tooth biomechanical behavior following endodontic therapy can be attributed to changes that occur at different levels: tissue composition, dentin micro- and macrostructure, and tooth structure.

Tissue composition

The loss of vitality is accompanied by a change in tooth moisture content,[7,8] which has a slight influence on Young modulus and proportional limit.[9] However, no decrease in compressive and tensile strength is associated with this change in water content.[9] The loss of moisture (9%) is attributed to a change in free water but not in bonded water.[7] Only one study did not show any difference in moisture content between vital and nonvital teeth.[10] No difference in collagen cross linkage was found in vital and nonvital dentin.[11] There is no other evidence of chemical alteration due to the removal of pulpal tissue.

Sodium hypochlorite and chelators such as ethylenediaminetetraacetic acid (EDTA), 1,2 cyclohexane–diaminetetra–acetic acid (CDTA), and ethylene–glycol–ether diaminetetra–acetic acid (EGTA), as well as calcium hydroxide commonly used for canal irrigation and disinfection, interact with root dentin, either with the mineral content (chelators) or the organic substrate (sodium hypochlorite).[12–14] Chelators deplete mainly calcium by complex formation and also affect noncollagenous proteins, leading to dentin erosion and softening.[13,15,16] Sodium hypochlorite exhibited a proteolytic action supposedly by extensive fragmentation of long peptide chains such as collagen.[17]

Dentin physical characteristics

Dentin microhardness and elasticity varied between peritubular and intertubular dentin and were also affected by location within the tooth (changes from dentinoenamel junction to mantle dentin); peritubular dentin presents a modulus of elasticity of 29.8 GPa, whereas intertubular dentin ranges between 17.7 GPa (close to pulp) and 21.1 GPa (close to root surface).[18–20] Most, if not all, of the decrease in hardness as the pulp is approached can be attributed to changes in hardness of the intertubular dentin.[20,21]

Dentin modulus of elasticity was considered to be in the range of 16.5 to 18.5 GPa.[22–24] However, recent measurements of Young modulus using a new optical imaging measuring device yielded lower values (10.4 ± 2.9 GPa)[25]; moreover, the literature review of Kinney et al reported large variations in the dentin modulus of elasticity.[26] Differences also were found between static (8.6 ± 0.86 GPa) and dynamic (14.3 to 15.8 GPa) modulus of elasticity measurements.[27] The changes in mineral density due to the variation in the number and diameter of tubules within the tooth also may explain variations in the properties of dentin. Actually, Pashley et al[28] presented a range of hardness values for dentin that were inversely related to dentinal tubule density. Ultra microindentation measurements also have shown significantly higher values for hardness and modulus of elasticity when forces were parallel to the tubules rather than perpendicular.[29] Differences in maximum strength and compressive strength were found to vary according to tubule orientation.[25] The ultimate tensile strength of human dentin was evaluated by direct tensile and diametral testing.[30] Ultimate tensile strength was the lowest when the tensile force was parallel to tubule orientation, showing the influence of dentin microstructure and anisotropy of the tissue. The literature, however, does not ascertain the possible influence of tissue maturation/aging and related reduction in tubule diameter and number[31,32] on dentin physical properties.

No or only minor differences in microhardness values were found between vital and nonvital dentin of contralateral teeth after 0.2 to 10 years.[33,34] The literature does not support a widely held belief that attributes particular weakness or brittleness to nonvital dentin. It also is believed that the progressive volume reduction of the pulp, replaced by secondary or tertiary dentin, could account for a reduced fracture resistance of aged, nonvital teeth; this assumption also is not supported by or even evaluated in the literature.

As mentioned previously, products used for canal irrigation and disinfection interact with mineral and organic contents and then to a significant extent reduce dentin modulus of elasticity and flexural strength[35,36] as well as microhardness.[37–40] On the contrary, disinfectants like eugenol and formocresol increase dentin tensile strength via protein coagulation and chelation with hydroxyapatite (eugenol); hardness, however, was not influenced by the latter products.[41]

Fracture resistance and tooth stiffness

The major changes in tooth biomechanics are attributable to the loss of tissue following caries lesion, fracture, or cavity preparation, including the access cavity before endodontic therapy. The loss of tooth structure during conservative access cavity preparation affects tooth stiffness by only 5%[42]; the influence of subsequent canal instrumentation and obturation either led to a reduction in the resistance to fracture[42] or seemed to have little effect on tooth biomechanics.[43] Logically, canal preparation should affect tooth biomechanics proportional to the amount of tissue removed and possibly also by the chemical or structural alteration triggered by endodontic irrigants.[35–40]

The largest reduction in tooth stiffness results from additional preparation, especially the loss of marginal ridges; the literature actually reports 14% to 44% and 20% to 63% reduction in tooth stiffness following occlusal and mesio-occlusodistal (MOD) cavity preparations, respectively.[43–45] The influence of residual structure on the stiffness and deformation under stress of endodontically treated teeth was additionally investigated[46,47]; it was shown that an endodontic access cavity combined with an MOD preparation resulted in maximum tooth fragility. The cavity depth, isthmus width, and configuration are then highly critical factors in determining the reduction in tooth stiffness and risk of fracture[46–49] (Fig 1).

The ferrule effect and a larger amount of residual tissue in general proved to increase tooth resistance to fracture.[50,51] Actually, a minimal 1-mm ferrule is considered neces-

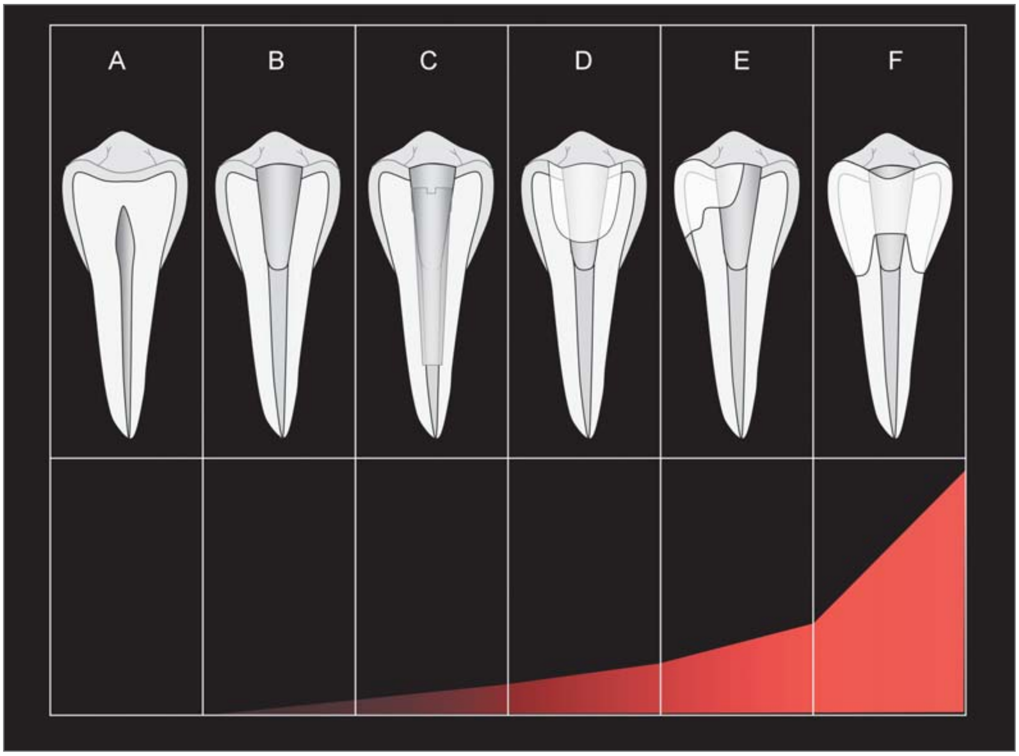

Fig 1 Comparative mechanical alterations due to endodontic therapy and cavity configuration. (A) Intact tooth; (B) endodontic access cavity and therapy; (C) post placement; (D) occlusal preparation; (E) conservative 2-surface preparation; (F) invasive 2- or 3-surface preparation. The red surfaces indicate modifications in stiffness and resistance to fracture related to aforementioned configurations.

sary to stabilize the restored tooth.[50] The width of preparation shoulder and crown margin do not appear to influence fracture strength.[52]

RESTORATIVE MATERIALS AND TECHNIQUES AND THEIR INFLUENCE ON TOOTH BIOMECHANICS

Physicochemical properties of restorative materials

Posts show varying modules of elasticity in relation with the force direction, in the case of anisotropic materials, ie, resin-fiber posts,[53] or behave rather similarly following different strain directions with isotropic materials such as metals and ceramics.[22,25,54] Metals and ceramics used for post fabrication present modules of elasticity that are markedly above that of dentin (110 GPa for titanium to 200 GPa for stainless steel and 200 GPa for zirconium to 300 GPa for aluminum oxide). The rationale for using stiffer or stronger materials has always been to strengthen the tooth. At present, however, this concept is questioned because of the existing limitations of adhesive procedures within the root canal[55–57] or between the post and the luting cement.[58] Large variations exist in regard to the physical and fatigue resistance of resin-fiber posts.[59] The static or dynamic behavior of resin-fiber posts depends on the composition (fiber type and density) as well as the fabrication process and, in particular, the quality of the resin-fiber interface. Posts that employ a silanization of fibers have been shown to behave much better under cyclic forces.[59] In an in vitro study examining physical properties of various posts, it was concluded that the ideal post design comprises a cylindrical coronal portion and a conical apical portion.[60]

The physical properties of the core material also can influence the performance of the prosthetic superstructure.[61]

There are, however, no minimal physical requirements for posts or restorative materials to be used for the restoration of a nonvital tooth abutment; there is only a growing trend to use materials whose mechanical properties are closer to those of dental tissues for post and core fabrication.[22,62]

Fracture resistance, tooth stiffness, and other monotonic mechanical tests

With cast posts and cores, a precise adaptation increases fracture resistance but at the same time increases the severity of the root damage, potentially leading to tooth extraction.[63] When using amalgam or gold restorations on endodontically treated teeth, covering cusps proved to increase the fracture resistance or tooth stiffness.[64,65] In the absence of cuspal coverage, resin composite restorations with adhesion to dentin and enamel showed a mechanical behavior (fracture resistance and stiffness) much closer to the unaltered tooth than did amalgam restorations.[64] However, it is not yet considered appropriate to restore endodontically treated teeth having 2 or 3 surface cavities with a conservative approach, without cuspal coverage.[43]

Comparison of the fracture resistance of teeth restored with either zirconium ceramic or resin-fiber posts revealed a higher resistance of teeth restored with fiber posts; in addition, teeth having ceramic posts failed mainly following post and root fractures,[66,67] whereas other specimens showed only fractures of the coronal reconstruction.[67] In another study, no difference was found in the fracture resistance of different post and core systems, but again a higher incidence of catastrophic root fractures was observed with ceramic posts.[68] Newman et al[69] reported that the resistance to fracture of teeth restored with gold posts was superior to those restored with resin-fiber posts; but likewise, more harmful fractures were observed in teeth with metal posts. Parallel posts also appeared more favorable in respect to root fracture patterns.[63]

Underneath full prosthetic reconstruction, titanium posts with composite core showed the highest resistance to fracture, followed by quartz-fiber and glass-fiber posts, with zirconium posts showing the least resistance[70]; but once again, catastrophic failures were observed only when the stiffer metal and ceramic posts were used. It was shown also that the presence of a crown attenuates the influence of the post material in the presence of a ferrule effect.[71]

Monotonic tests were designed to evaluate the influence of different materials, assemblages of materials, and restorative techniques on tooth resistance to extreme stress; this approach mimics very specific failure types or stresses, such as those observed in trauma, under abutments of removable dentures or posts and cores during the removal of a provisional crown. In fact, most clinical failures resulting in material and tissue breakdown or interface separation can be ascribed to physiologic masticatory or parafunctional forces when repeated over long periods of time, also known as fatigue stress,[72–75] which will be described in part 2 of this literature review.

Simulation of occlusal strains and masticatory function

At this level, attempts are made to simulate and monitor, directly or indirectly, the development and distribution of functional stresses into the tooth-restoration system using different technical and methodological means.

Photoelastic studies. Cemented posts caused less stress than do threaded posts.[76] The post design proved also to be an influential factor in photoelastic studies. Cylindrico-conical posts and flat thread and grooves induced a more favorable stress distribution with clearly more slight fringes at the apex, whereas merely conical posts acted as a wedge under increasing load.[77] In another study, cylindrical posts demonstrated high apical stresses on vertical or inclined loading.[78] In addition, the larger the post diameter, the more stress generated in the root.[79]

Regarding the influence of the coronal buildup, it was shown that stiffer core material, ie, cast gold versus resin composite, maintains stresses in the coronal region, lowering the load in the apical zone.[79]

A photomechanical investigation combining fractography and photoelasticity revealed that planes of stress concentration of the photoelastic model coincided with the plane of fracture of restored nonvital teeth.[80] Interestingly, a ductile response to fracture propagation was observed at the inner dentin, whereas outer dentin displayed a brittle response to fracture propagation; this finding is in accordance with the aforementioned description of dentin microstructure.

However, because photoelastic models do not reproduce or mimic the essential physical characteristics of dental tissues and cannot simulate the complex physicochemical strains of the oral environment, it does not represent the ideal tool for modeling the variety of interactions between dental restorations and tooth substrate. This technique progressively has been replaced by finite element analysis.

2-Dimensional finite element analysis. When a nonadhesive approach (cast gold post and core) was used, the greatest stress concentration appeared at the post-dentin interface, whereas with fiber-reinforced resin composite posts and cores, stresses rose in the cervical region and showed the lowest peak inside the root due to a stiffness close to that of natural dentin.[81] In contrast, Eskitascioglu et al[66] explained that more stress was being transferred to supporting bone and root structures with fiber-composite laminate post and core, while more stress was accumulating inside cast metal post and cores (Figs 2a and 2b). They "surprisingly" concluded that the tested metal substructure potentially has a better protective role for the tooth and surrounding tissues, whereas the fracture test performed in the same study yielded opposite findings. In another study,[82] it was shown that post and core have only a moderate reinforcement effect and that a core with a long parallel-sided post, but inferior to two-thirds of the root length, distributes the stress widely in the restoration and tooth structure, resulting in the lowest peak stresses. A small diameter post also reduced stress. In addition, the direction of the load had a greater influence on stress than dowel design.[82] The aforementioned results suggest that one parameter alone, ie, material, post design, or dimensions, cannot serve to establish clear clinical guidelines for the selection of the ideal post and core technique using this experimental methodology.

3-dimensional finite element analysis. Lertchirakarn et al[83,84] modeled roots of mandibular incisors in 3 dimensions and correlated the finite element analysis with strain measurements and fracture patterns of natural tissues; they demonstrated that root curvature is more influential than root transverse anatomy regarding fracture pattern and stress concentration. They found as well that tensile stresses peak on the proximal surface in relation to dentin thickness.

Again, it was shown that the tooth reinforcement resulting from the use of posts is rather insignificant, the stress distribution within dentin being almost identical with or without a post.[85] Pierrisnard et al[86] showed that stresses in the cervical region are reduced by the presence of a post, especially those with a high modulus of elasticity, even in the presence of residual coronal dentin (see Fig 2a). They also demonstrated the importance of the ferrule effect to reduce cervical stresses and increase the resistance of the restored tooth. In fact, the ferrule effect is so significant that it practically cancels the influence of the underlying materials. In another study, by Holmes et al,[87] it was shown that peak dentin shear stresses occur adjacent to the post at midroot and are elevated as the post length decreases; post length, however, did not influence distribution of tensile and compressive stresses. Peak dentinal stresses occurred in the gingival third of the facial root surface.

Other authors commenting on a global approach to restorative dentistry[88] suggested that an ideal restorative material should exhibit a Young modulus identical to the tooth structure. Resin composite appears to be the ideal replacement material for dentin.

Simplifications of finite element method (FEM) models, however, cannot be avoided. In fact, in the majority of 2- or 3-dimensional FEM studies, dentin and enamel are modeled as isotropic, homogenous, linearly elastic substrates[89–92] despite their intrinsic anatomic anisotropy (tubules and prisms) and subsequent variations in microhardness

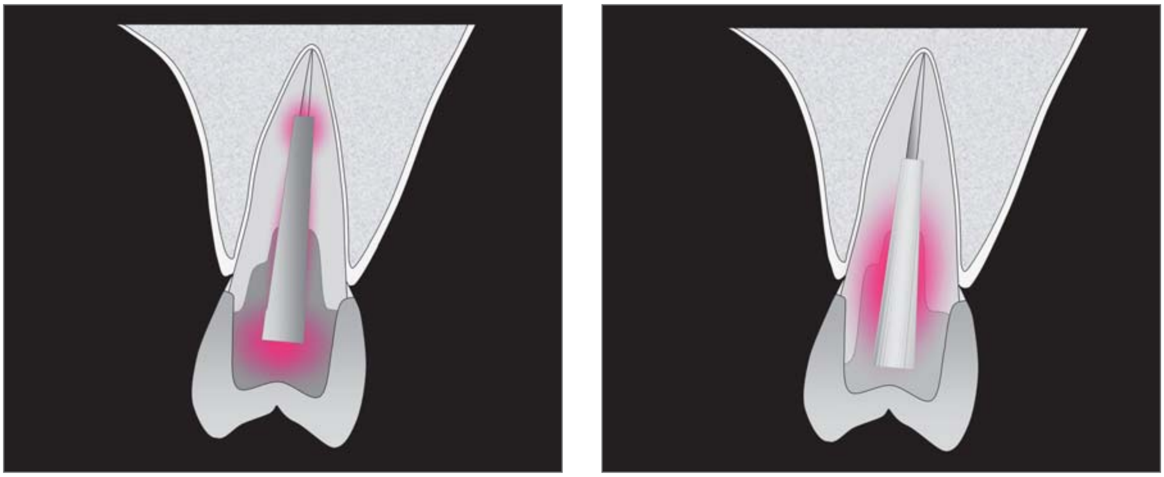

Fig 2 *(a)* Stress distribution within a metallic post and core foundation and residual tooth structure, according to photoelastic and FEM studies. The post is cemented and usually penetrates the root more apically. Functional stresses accumulate inside the foundation, slightly around the post and further inside the canal, around the post end; there is less stress buildup in the cervical area compared to that with a fiber post, as shown in Fig 2b. This configuration more ideally protects the coronocervical structures, but when failing, results in severe, untreatable root fractures. *(b)* Stress distribution within a fiber post/composite foundation and residual tooth structure, according to photoelastic and FEM studies. The post is bonded to the canal walls and penetrates the canal less deeply. Functional stresses accumulate mainly around the post in the cervical area. This configuration protects the cervical area less efficiently but tends to prevent untreatable root fracture. The presence of ferrule effect appears to be mandatory.

and elastic behavior.[18,91,92] Actually, elastic properties (Young modulus and Poisson ratios) of peritubular and intertubular dentin greatly differ.[93] However, this anisotropy is at a microscopic scale, whereas the tooth model is more macroscopic[94]; therefore, modeling dentin as an isotropic continuum fortunately is not totally erroneous. A few finite element analysis studies, however, have taken into consideration the effect of enamel anisotropy.[95,96] The behavior under stress of some restorative materials also needs to be simplified.[96] Interfaces also are assumed as being continuous,[87,89,97] an assumption which is not realistic, even for adhesive techniques.[56,98] Only one study reported the use of a model with partial or no bonding of the composite core, trying to fit the results of FEM to those obtained through fatigue studies.[99] Moreover, FEM studies at present are unable to simulate the dynamics and complexity of cyclic masticatory function.

The crucial advantage of finite element analysis then is to quantify and visualize the distribution of stresses within the restored tooth in reaction to defined strain levels and directions, without the influence of variables inherent to biologic materials.

CONCLUSIONS AND BASIC RESEARCH-DRIVEN TREATMENT RECOMMENDATIONS

The impact of vitality loss appears moderate to negligible concerning moisture or physical properties of dentin such as microhardness, modulus of elasticity, and fracture toughness. Changes in tubule density were reported but depend mainly on the root level (decreases toward the apex) and tooth age. The preparation of an access cavity, canal enlargement during endodontic procedures, and use of specific chemicals and post placement, however, significantly reduce tooth strength. In fact, tissue conservation is the most critical issue when dealing with a nonvital tooth. Preserving intact structures throughout the tooth and especially preserving and maintaining cervical tissue to create a ferrule effect are crucial to optimize the biomechanical behavior of the restored tooth. Regarding potential adhesion to residual tooth structure, one has to be aware of the influence of endodontic therapy, since chelators, sodium hypochlorite, and calcium hydroxide significantly affect dentin quality.

The use of posts seems not to be mandatory for the restoration of a nonvital tooth, unless an insufficient retention of the core is obvious. Posts with physical properties close to those of natural dentin (resin-fiber posts) currently are the preferred option because they have physical properties closer to dentin than do metals or ceramics. Nevertheless, the need to have a rigid foundation to protect the prosthetic restoration (reduced flexure and risk of decementation or breakage, especially when using all-ceramic restorations often has been mandated by clinicians. Using stiffer posts (metals or especially ceramics), however, would be beneficial for the rigidity of the tooth and stability of the prosthetic restoration, but only if a perfect cohesion between all constituents could be attained, which is not yet possible. In addition, since no element or finding suggests that the natural dentin core is inappropriate, the use of materials with dentinlike properties currently appears to be the most suitable approach.

In addition to the aforementioned decision-making guidelines, one should not omit additional and essential clinical elements such as caries risk, occlusion determinants (canine or group guidance, type of occlusion, overjet, and overbite) and the presence or absence of parafunction, which can markedly influence the biomechanical potential or risk of the intended restoration.

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