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In Vitro Performance of Class I and II Composite Restorations: A Literature Review on Nondestructive Laboratory Trials—Part I

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Clinical Relevance

In vitro research remains of primary importance to selecting and validating the techniques and products to be used *in vivo*. However, the clinical predictive value of such tests needs to be appraised and ranked to provide meaningful help toward the clinical decision-making process.

ABSTRACT

Posterior adhesive restorations are a basic procedure in general dental practices, but their application remains poorly standardized as a result of the number of available options. An abundant number of study hypotheses corresponding to almost unlimited combinations of preparation techniques, adhesive procedures, restorative options, and materials have been described in the literature and submitted to various evaluation protocols. A literature review was thus conducted on adhesive Class I and II restorations and nondestructive *in vitro* tests using the PubMed/Medline database for the 1995-2010 period. The first part of this review discusses the selected literature related to photoelasticity, finite element analysis (FEM), and microleakage protocols. Based on the aforementioned evaluation methods, the following parameters proved influential: cavity dimensions and design, activation mode (light or chemical), type of curing light, layering technique, and composite structure or physical characteristics. Photoelasticity has various limitations and has been largely (and advantageously) replaced by the FEM technique. The

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results of microleakage studies proved to be highly inconsistent, and the further use of this technique should be strictly limited. Other study protocols for adhesive Class II restorations were also reviewed and will be addressed in part II of this article, together with a tentative relevance hierarchy of selected *in vitro* methods.

INTRODUCTION

The use of posterior adhesive restorations as a primary treatment for caries or as a substitution for metal-based restorations remains a basic procedure in general dental practices.[1-3] However, it is presently a poorly standardized treatment as a result of the number of available options for nearly each clinical step involved. It generally is accepted that small cavities will be restored with a direct technique, likely using an incremental approach, and that multiple large cavities will be restored with an indirect technique.[4] Anything in between these two opposite clinical situations currently lies in a gray zone, thus leading to countless "speculations" and concepts often founded on limited evidence.

The clinician must thus consider which is the ideal adhesive approach and system, whether or not to use a base or liner, which is the best restorative material, and which restorative approach (direct or indirect) should be used. When a direct approach is chosen, thought must then be given to what type of layering technique (if any) should be applied. This represents a substantial number of combinations, which tremendously complicates the clinical and operative choices. Searching for literature evidence neither leads to a straightforward answer nor helps in making easy decisions as a result of the overwhelming number of studies evaluating Class II restoration quality and behavior. This abundant literature deals with various *in vitro* and *in vivo* studies and requires a strategy to identify the most relevant information. While an evidence hierarchy has been established for *in vivo* studies in biomedical science,[5-8] the same thinking process has not yet been applied to *in vitro* research.

While everyone agrees that clinical studies ultimately confirm the validity of any treatment option, the impact of *in vivo* research remains counterbalanced by many factors. These include the number of available restorative protocols and products but also by several other inherent limits and drawbacks related to patient selection, sample size, number and qualification of operators, evaluation criteria and methods, the significant resources required, and, last but not least, the time frame.[1-3] In regard to this latter point, and despite the absence of a formal consensus, clinicians and researchers have logically suggested running medium- to long-term studies to ascertain operative protocols and material choices. Several authors have then proposed that evaluation periods should not be shorter than three to five years.[9,10] Regrettably, the rapid turnover of dental product and application protocols tends to lessen the validity of otherwise-legitimate long-term studies. This is why a number of preclinical, *in vitro* evaluation protocols were developed to overcome the aforementioned clinical trial boundaries.[9-11] Recent literature reviews on the *in vivo* performance and longevity of various posterior restorations have identified mainly four kinds of failures (with the exception of early failures associated with faulty material handling), and these are marginal defects or secondary caries (interfacial failures) and restoration fractures or excessive wear (material failures).[1,3,12,13] With regard to posterior composite restorations, interfacial failures appeared to prevail in a large number of studies.[12,13] This actually explains why the majority of protocols applied to evaluate the *in vitro* performance of adhesive restorations focus on phenomena that influence adhesive interface quality and stability. However, the interest and real predictive value of the many laboratory tests should be discussed and their possible clinical relevance estimated more precisely.

Therefore, the purpose of this review was first to search for and select *in vitro* studies on Class I and II adhesive restorations using nondestructive tests, according to the research protocol and hypothesis. The second objective was to critically appraise selected articles and to propose a classification and hierarchy of laboratory protocols based on the quality, quantity, and consistency of the evidence, in particular, toward a likely clinical significance. The third resulting objective was to draw conclusions and recommendations in regard to the best restorative protocols and materials based on the results of nondestructive *in vitro* evaluations of adhesive posterior restorations. The first part of this review will detail the search strategy and classification of selected references according to study protocol and hypotheses as well as an appraisal of photoelasticity, finite element analysis (FEM), and microleakage studies.

MATERIALS AND METHODS

Search Strategy

The search strategy included a review of the PubMed/Medline database, with use of the following primary key words: *in vitro,* Class II, posterior composites, inlays and onlays, tooth colored, and composite. Additional key words related to study hypothesis (such as cavity configuration, polymerization, or light-curing, or to study methodology, such as finite element analysis, photoelasticity, leakage and microleakage for part I of this review, and resistance to fracture or deformation, shrinkage stress, tooth deformation, bond strength and microtensile bond strength, marginal and internal adaptation for part II of this review) were used to identify all existing references. The search was conducted with the limit "Dental Journal." The review was conducted from 1995 to 2010. Perusal of the references of relevant articles allowed completion of the review (references of the references). A few older "major" references were used to supplement these aforementioned resources when appropriate. The selection and analysis process led us to study exclusion in cases of insufficient group description, undefined hypothesis, operative protocol, or results, including statistical analysis. The articles were first classified according to the experimental protocol, with each one corresponding to a specific review table, as follows:

I. Photoelasticity,
II. FEM (two dimensional [2D]/three dimensional [3D]),
III. Microleakage,
IV. Deformation resistance and fracture resistance to cyclic loading (mere fracture testing was not considered),
V. Shrinkage stress and tooth deformation,
VI. Bond strength (microtensile, tensile, and shear tests), and
VII. Marginal and internal adaptation.

Subsequently, for each experimental protocol and table, selected references were then subclassified according to the parameters/hypotheses investigated. For microleakage, bond strength, and marginal adaptation protocols, the type of restoration was also taken into account (direct and indirect composite restorations only or comparisons between direct and indirect techniques), together with the most relevant subparameters identified within selected studies. The references strictly related to indirect ceramic and CAD-CAM/Cerec® (Sirona, Bensheim, Germany) restorations or restoration fit, as well as those dealing with restorations of deciduous teeth, were excluded from this review. In addition, wear tests and studies measuring restoration fracture resistance to monotonic stress/loading (in general, all kinds of destructive tests) were not taken into consideration for this literature review.

Appraisal and Rating of Study Protocols and Results

The overall strength of evidence for clinical topics and reviews is usually defined by three factors: the quality, quantity, and consistency of the evidence. This approach, introduced in 1994,[14] is now well established and is largely used to develop practice guidelines and other health-related policy advice.[8,15-18] The "quality" refers to a study protocol that follows strict rules to limit selection, measurement, and confounding biases. The "quantity" refers mainly to the number of studies having evaluated the same topic and the overall sample size across all included studies. The "consistency" is defined by the extent to which similar findings are reported using similar or different study designs.[8] This review tentatively applied this evidence "rating approach" whenever possible and when appropriate for an *in vitro* research field.

I. Photoelasticity—Photoelasticity aims to visualize stresses generated by different restorative techniques using composite[19-22] or resin,[23,24] placed in different substrates (such as transparent composite or resin, composite, and bovine teeth).[21,25] After sectioning the samples, stress patterns and magnitude within the transparent material (restoration or cavity) are evaluated under a polarizing microscope. The photoelasticity studies that were reviewed are presented in Table 1.

The use of bovine teeth as a substrate proved inadequate for photoelasticity studies when a bulk technique was applied because of large gap formation, which lowered stresses.[19,21] Self-curing and light-curing composites showed similar stress distribution patterns, while stress magnitude and development proved significantly different. Interestingly, maximal average stress in a self-curing material was only 12 MPa, vs 23 MPa in a light-curing material.[19-21] Stress distribution and magnitude also proved to be influenced by cavity depth (less stress in a shallow cavity) and internal cavity design (less stress with internal bevel compared to box-shaped cavity).[22] No differences in stress distribution or magnitude appeared between butt or round beveled margin designs.[22] In two other studies,[23,24] shrinkage stresses generated by a bulk technique proved surprisingly lower than those generated by different incremental techniques' but this later finding is in disagreement with those of several marginal adap-

Table 1: *Selected Literature References for Photoelasticity*

Kinomoto and Torii, 1998 [19]
Kinomoto and others, 1999 [20]
Kinomoto and others, 2000 [21]
Kinomoto and others, 2003 [22]
Jedrychowski and others, 1998 [23]
Jedrychowski and others, 2001 [24]
Wiegand and others, 2007 [25]

tation and bond-strength studies, as reviewed further in this article.

Conclusion: Photoelasticity

The main drawback of the photoelasticity approach is that the use of resin or composite replicas does not properly mimic the physical properties and behavior of natural teeth, as it produces a more perfect interface (composite-composite or composite-resin) than actually occurs in clinical conditions. The use of bovine teeth as a potential substrate also proved unsuccessful, with excessive gap formation, and, therefore irrelevant, low stress buildup within the restoration was observed. Furthermore, the photoelasticity approach is unable to mimic the effect of repeated functional or thermal stresses, which are responsible for restoration fatigue, the dominant pattern involved in clinical failures.

The protocol quality was considered "low," as was the quantity of evidence. The consistency is also problematic for photoelasticity, making the overall strength of evidence insufficient. FEM is therefore more widely used to visualize and estimate the magnitude of polymerization contraction stresses in Class II restorations.

II. Finite Element Analysis—The FEM or analysis originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. Its development can be traced back to the work of Alexander Hrennikoff[26] and Richard Courant in 1943.[27] While the approaches used by these pioneers are dramatically different, they share one essential characteristic: the mesh discretization of a continuous domain into a set of discrete subdomains, usually called elements. This technique appeared in the study of composite polymerization stresses and restorative dentistry in the late 1980s[28,29] and has since become a major tool for analyzing and understanding those phenomena. The FEM studies that were reviewed are presented in Table 2.

Model validation, natural tooth structure, and function

The micro–computed tomography scan was considered an effective method with which to develop 3D FEM models.[30,31] Different studies also evaluated the development and distribution of stresses within normal posterior tooth structure to be used as references for FEM analysis. It was first shown that the behavior of enamel and dentin under different load axes was independent.[32] The distribution and level of stresses also proved to be influenced by force direction (working or nonworking movements)[33] as well as by the elasticity modulus of the food morsel.[34] Maximal stresses were found in the occlusal enamel, the central groove of maxillary molars, and the lingual cusp of mandibular molars.[33,34] Supporting cusps were generally well protected during both working and nonworking movements, while nonsupporting cusps sustained mainly tensile stresses.[33] The chewing of nonhomogeneous morsels was also considered to produce the least favorable condition.[34]

For restored teeth, the FEM approach was validated by comparing simulated stresses to those measured on natural teeth using different restorative solutions.[30,35] It was then considered valid to use a linear elastic approach based on the post–gel shrinkage concept to calculate residual stresses in a tooth restored with composite.[35]

Cavity design and dimensions

The relationship among cavity design, volume, and contraction stress was clearly established more than 20 years ago by the team of Davidson and Feilzer.[28,36-38] However, at that time it proved impossible to visualize and precisely quantify stress distribution at interfaces or within the restored tooth structure. Since then, FEM studies have enabled a considerable progression of our understanding of stress development within complex material assemblages and restorative models.

Cast gold restorations, unbonded or bonded composite MOD restorations, and cavity size all proved influential factors for stresses.[39,40] The unbonded condition was, however, less favorable and more prone to generate damaging stresses for the tooth. In cast gold restorations, depth was also the most critical factor governing stress elevation in enamel, while interaxial thickness (cavity floor width, in-between proximal preparations) was the most critical factor for dentin.[39] The influence of composite shrinkage stress in different Class I and II cavity geometries was evaluated in natural teeth and theoretical FEM models. The behavior of both

Table 2: *Selected References for Finite Element Analysis (FEM)*

Model validation, natural tooth structure and function	
	Verdonschot and others, 2001 [30]
	Magne, 2007 [31]
	Goel and others, 1990 [32]
	Magne and Belser, 2002 [33]
	Dejak and others, 2003 [34]
	Versluis and others, 2004 [35]
Cavity design and dimensions	
	Morin and others, 1988 [28]
	Versluis and others, 2004 [35]
	Davidson and others, 1984 [36]
	Davidson and de Gee, 1984 [35]
	Feilzer and others, 1987 [36]
	Lin and others, 2009 [37]
	Li and others, 2010 [38]
	Lin and others, 2001a [39]
	Lin and others, 2001b [40]
	Fennis and others, 2003 [41]
	Fennis and others, 2005 [42]
	Xu and others, 1999 [43]
	Hubsch and others, 2002 [44]
	Li and others, 2010 [45]
	Lin and others, 2009 [46]
Influence of restorative technique, material properties, and/or material comparisons	
	Versluis and others, 1996 [47]
	Spears, 1998 [48]
	Kowalczyk, 2009 [49]
	Kuijs abd others, 2003 [50]
	Ausiello and others, 2001 [51]
	Toparli and others, 1999 [52]
	Arola and others, 2001 [53]
Interface and adhesive systems	
	Lin and others, 2001 a [40]
	Ensaff and others, 2001 [54]
	Ausiello and others, 2002 [55]
Comparative behaviour of resin composite and ceramic restorations	
	Magne, 2007 [31]
	Magne and Belser, 2003 [56]
	Ausiello and others, 2004 [57]
	Belli and others, 2005 [58]
	Yamamoto and others, 2007 [59]
	Magne, 2010 [60]
	Jiang and others, 2010 [61]
	Yamanel and others, 2009 [62]
	Magne and Oganesyan, 2009a [63]
	Magne and Oganesyan, 2009b [64]

Table 2: Continued.

Analyses and effect of stresses	
	Versluis and others, 2004 [35]
	Lin and others, 2001a [39]
	Ensaff and others, 2001 [54]
	Versluis and others, 1998 [65]
	Fenner and others, 1998 [66]
	Li and others, 2008 [67]
	Pantelic and others, 2007 [68]

experimental (same restorative configurations tested on natural teeth with stress gauge) and FEM models proved well correlated.[35] Shrinkage stresses appeared to be dependent on the configuration and size of restorations, with larger Class II restorations resulting in lower stress levels in the restoration and tooth-restoration interface as a result of the increased tooth deformation and stresses. Therefore, it can be concluded that shrinkage stress cannot be based on composite properties alone but depends also on the restoration configuration and dimensions as well as the restorative procedures. The FEM model of cusp replacing restorations on premolars has also shown the superior stress resistance of full occlusal coverage compared to single cusp coverage. Failures of analogous restorations made on natural teeth in such situations were mainly of an adhesive nature.[41,42]

Cavity margins with 60° to 75° (compared to 90°) of inclination[43] and rounded or beveled margins (compared to unbeveled cavity margins)[44] proved, respectively, to offer the best resistance to vertical and lateral forces and a significant reduction of stresses along their adhesive interface. Li and coworkers[45] used a simplified tooth model with uniform E-modulus (6 GPa) in an attempt to optimize the restoration shape for stress management, using a load of 400 N. Using this model, a T-shaped cavity (larger occlusal opening and reduced bucco-lingual width of the cavity base) appeared to offer the most favorable design for MOD restorations on premolars. However, such a design is, unfortunately, clinically irrelevant on the basis of a geometric incompatibility with usual caries or restoration anatomy. Using an indirect composite inlay model on a premolar, Lin and coworkers[46] showed that the most influential factors for stress in indirect restorations were load (magnitude and direction) followed by cavity depth. Other factors, such as isthmus depth, interaxial thickness, and resin thickness, all had an insignificant impact on stress level. This study did also show that low elastic modulus resin cement contributed to reducing the stresses that were transmitted to the tooth.

Influence of restorative technique, material properties, and/or material comparison

A first study[47] compared stress buildup and tooth deformation resulting from a MOD direct composite restoration using bulk placement or different incremental techniques and, surprisingly, showed an advantage of the bulk approach in contrast to the large majority of other *in vitro* studies (see "Microleakage" and "Marginal adaptation" sections) that have indicated the use of incremental techniques to minimize the negative consequences of polymerization shrinkage. Another FEM study[48] reached the opposing conclusion, indicating that the use of an incremental technique does help to control stresses in direct restorations. More recently, an interesting study[49] evaluated the impact of increment geometry in horizontal layering technique (perfectly horizontal or concave shape) as well the presence of a pre-layer (lining extending up to half-enamel thickness occlusally) in regard to the stresses developing in the adhesive interface and dental tissues. It was shown that concave layers associated with either regular (same thickness, up to half-enamel thickness) or edge shape (thinning of the lining toward half-enamel thickness) composite pre-layers were highly successful in reducing polymerization stresses. In larger composite buildups with cusp replacement, the bulk chemical curing technique induced less stress than did bulk or layered light-cured restorations. In this study, maximal stresses were observed at the restoration interface and at the cervical part of the remaining cusp.[50]

The stiffness of composite resins also proved to be an influential factor governing stress development and tooth deformation as a result of composite shrinkage or functional loading. A stiff material induces more tooth deformation and increases preloading stress (stress state before simulated load) following polymerization shrinkage, while on the contrary, a low-elastic modulus composite induces less preloading stress but allows for more deformation under load.[51] In addition to the aforementioned parameters, the position of load also influences stress development.[48] Interfacial problems are more likely with a low restoration modulus (10-20 GPa), while in high-modulus restorations, intercuspal stresses increase. The optimal E-modulus seemed, then, to be around 30 GPa.[48] This suggestion is, however, irrelevant to existing resin composite or ceramic systems used in restorative dentistry, which have, respectively, lower or higher elasticity modules.

The comparative behavior of sandwich restorations made of glass ionomer (GI) and amalgam or GI and composite showed that residual stresses were, respectively, of compressive or tensile nature.[52] The maximum compressive stress occurred at the occlusal margin in the amalgam and decreased toward the cervical margin line. Conversely, in composite resin, the stress distribution was of a tensile nature and increased toward the cervical margin.[52] Overall stress magnitude and location were related to the type of restoration, non-adhesive metal based (amalgam) or adhesive, composite restoration.[53] In both restoration types, maximal stresses were found at the interface but with lower magnitude in the adhesive restoration. Maximal stresses appeared in locations different from those identified in the previous study, with the highest stresses at the pulpal floor line angles for amalgam restorations and along occlusal lingual margins in composite restorations. Stress distribution was, however, only minimally influenced by occlusal load direction.[53]

Interface and adhesive systems

The adhesive interface proved to play a major role in absorbing contraction stresses (and supposedly functional stresses as well) by elastic deformation.[54,55] It was shown that stress magnitude and cusp deformation increased proportionally to adhesive layer stiffness, and, therefore, failures were more likely to develop at the interface, as it physically remains the weakest component of the system.[54] Moreover, in addition to a reduction of adhesive layer E-modulus, increasing the adhesive layer thickness would be an alternative way to reduce interfacial stresses. Similarly, cusp movement under load was inversely proportional to composite rigidity and proved again the significant impact of the elasticity of restorative components on stress development and potential incidence or type of failure.[55]

Lin and coworkers[40] evaluated the impact of adhesive interface quality (bonded or "unbonded" interface) on the fracture potential of different cavity depths and loads. As expected, they observed that the more realistic "unbonded" configuration presented an increased risk for fracture.

Comparative behavior of resin composite and ceramic restorations

The type of restoration (inlay or onlay), the restoration size (large or small), and material type (composite or ceramic) largely influenced stress magnitude and direction as well as tooth deformation.[31,56-59] Under load, interfacial stresses were mainly of a tensile nature in inlay restorations, while they were of a compressive nature in onlay restorations.[56] Rigid porcelain restorations, compared to less rigid composite, featured more stress at the occlusal surface but reduced crown deformation and stress magnitude at the adhesive interface.[56] Using a model of a nonvital tooth with an overlay restoration, the material again proved to influence the stress magnitude in both force levels tested (200 or 700 N). Porcelain restorations showed a stress peak measuring 30%-50% higher than composite overlays, and differing maximal stress locations within the tooth were observed.[60] This study indicates that composite restorations with a much lower E-modulus have a better potential to reduce forces transmitted to the residual tooth structure.

In a report[61] evaluating the stress distribution in molars restored with inlays and onlays made of gold, composite, or ceramic, both in vital and nonvital tooth configurations, much higher stresses were associated with the nonvital tooth configuration and inlay restoration. The stress differences in dentin at the preparation floor associated with the restorative material were extremely small, but lower absolute values were observed in composite restorations. However, another FEM study led to opposing conclusions. Using a vital tooth model and 200 N force applied on four different occlusal spots, materials with low elastic modulus values transferred more functional stress to the tooth structures, and the onlay design protected tooth structures more efficaciously than did the inlay design.[62]

For indirect restorations, the hybrid layer and cement act as a stress dissipater, the efficacy of which is proportional to their elastic deformation potential.[57,58] Interestingly, ceramic inlays luted with a high E-modulus cement failed to distribute stresses properly.[57] In general, porcelain restorations under load tended to collect stress inside their body, while composite restorations transferred more strains to the surrounding tissues.[58] The use of different composite liners also influenced the tensile interfacial stresses in composite or porcelain onlays. It was observed that stresses increased with a low-elasticity modulus base, and it therefore seems appropriate to use high-elasticity base materials.[59]

Cusp deformation and recovery under load proved to be influenced by cavity extent and restorative material (composite or porcelain).[31] Deformations ranged from 0.4 μm for an unrestored tooth up to 9-12 μm and 12-21 μm, respectively, for MOD or endo access cavities. Using a premolar model, the same author measured cusp widening induced by load in different cavity types (slots, MO, or MOD)[63] and then for MOD composite and porcelain inlays, according to different contact zones.[64] It was then concluded that maintaining the residual tooth "bridge" in between slots or a proximal ridge has the potential to limit tooth deformation.[63] Moreover, the stiffness of the porcelain restoration resulted in a superior tooth stabilization effect, which was observed by reduced intercuspal deformation.[64]

Analyses and effects of stresses

The impact of curing light direction or curing mode on composite polymerization shrinkage proved less significant than expected, and, contrary to widespread belief, composite does not seem to shrink toward the light.[65] In fact, the factor that proved the most influential on shrinkage direction was the layer and cavity configuration factor.[65] Stresses induced by temperature changes (from ambient to the simulated contact with an imbibing liquid at 48°C) were found to be of a tensile nature, ranging between 7.4 and 8.6 MPa at two seconds and 9.2 and 11 MPa at eight seconds.[66]

In an attempt to analyze apparent inconsistencies found in some FEM studies, Li and coworkers[67] approached the problem of composite polymerization stresses with an analytical solution using basic mathematical equations to describe the behavior of a simplified, cylindrical, Class I self-curing composite model. They pointed out again the influence of material shrinkage and Young's modulus to govern stress development. They also reported that stresses deep inside the restoration are higher than those at the restoration surface, which concentrate at the restoration margins. However, part of their protocol hypothesis included the existence of a perfect adhesive interface and linearly elastic tooth model. These factors represent a great divergence from clinical reality and may lead potentially to irrelevant study conclusions, such as the fact that the restoration volume has almost no influence on residual stresses. Pantelic and coworkers[68] measured tooth deformation in bulk Class I and II composite restorations by holographic interferometry and then evaluated related stresses in simplified FEM models. They observed that intercuspal deformation was in the magnitude of 2 μm in Class I and up to 14 μm in Class II restorations, while stresses varied between 50 MPa in Class II and 100 MPa in Class I restorations. This has the obvious potential to damage the restoration interface or even the tooth structure itself, considering that average interfacial bond strength to dental tissues, such as enamel tensile strengths, lie within a range of 15 to 25 MPa. These values were of a relatively high magnitude and close to those observed by Versluis and coworkers.[35] However, in other FEM studies,[39,54] composite contraction stresses in similar conditions were in a lower range (20 to 40 MPa).

Conclusion: FEM studies

Within the limitations of this study protocol, the most relevant conclusions are the following:

- Results of 3D FEM models were validated by testing similar restorative configurations in natural teeth by strain gauge.
- Stress buildup in direct restorations is influenced by cavity design and dimensions as well as layering technique (geometry and configuration of layers) and material physical properties (mostly stiffness).
- A stiff direct material increased preloading stress after placement but reduced deformation under functional loading. In addition, lower E-modulus adhesives and cements reduce stress at the tooth-restoration interface.
- Restoration approach (adhesive vs nonadhesive) influences stress, with the highest stresses found at the pulpal floor line angles for amalgam and at the occlusal margins for composite restorations.
- A bevel or round chamfer reduces stress compared to a nonbeveled, butt preparation.
- Ceramic restorations reduce tooth deformation under load but show overall higher peak stresses. A "high" E-modulus composite (around 20 GPa) seems to have the best biomechanical behavior among all restorative materials in both vital and nonvital tooth configurations.

Conclusion: FEM methodology

FEM is a crucial model to study the localization and magnitude of stresses in unlimited restoration configurations and material combinations, with reproducible load conditions and tooth anatomy. This is considered an unparalleled advantage compared to any other experimental method using natural tooth substrate. However, one drawback observed in some FEM studies is the simulation of nonphysiological forces, which limits the possible impact of modelized stresses on interfaces or tooth substrate (adhesive or cohesive failure). Moreover, FEM models cannot perfectly replicate the biomechanical "complexity" of the tooth-restoration whole, such as the differential adhesion patterns and anisotropy of dental substrates. 2D FEM models also represent a simplification of *in situ* conditions. A final observation is that to date, and as is the case for photoelasticity, dental FEM studies generally do not replicate cycling stresses and the effect of moisture. This is significant, as both of these phenomena have a major influence on restoration behavior and performance.

The absence of biological variability clearly supports the further use and development of this research model, although major limitations still exist in terms of possible clinical implications. The quality of evidence can consequently be considered satisfactory when using the latest 3D FEM models and taking into consideration the precise context of each study hypothesis. The quantity of evidence is, on the contrary, rather limited (as a result of the large number of study hypotheses), as is the consistency of the evidence (as a result of former primitive models or the 2D approach). This latter restriction should, however, recede with constant technology improvements.

III. Microleakage—The microleakage studies that were reviewed are presented in Table 3.

Comparison of restorative and layering techniques

Incremental and centripetal (layering from depth to surface) techniques showed a reduction in microleakage in cervical dentin compared to bulk-filling in numerous studies[69-73]; however, the use of various restorative techniques had no influence on microleakage at enamel margins.[74,75] Overall, less microleakage was observed at enamel margins compared to cervical dentin.[73,74,76-83] When comparing two existing curing modes of a comparable composite technology, the light-curing material produced less leakage than the self-curing one.[84]

Other restorative variables (cervical margin position, cavity dimensions, matrix systems, etc)

The application of different matrix systems did not influence enamel microleakage, while the use of a "collimator or transmitting" cone reduced leakage at dentin margins, compared to an oblique layering technique using a translucent matrix.[69] In another trial,[73] the application of a centripetal technique and a clear matrix reduced dentinal leakage compared to metal matrices. In another study,[77] the use of "collimator or transmitting cone" applied with pressure against the composite surface reduced microleakage in enamel but not in dentin. Two other studies[75,85] did not reveal any difference in dentin microleakage due to the matrix system.

With regard to the adhesive application, it was shown that the type of primer solvent was an influential factor for dentin microleakage but not for enamel. Similarly, an improper removal of water remnants following etching increased dentinal leakage.[83]

Table 3: *Selected References for Microleakage*
Comparison of restorative and layering techniques
Neiva and others, 1998 [69]
Poskus and others, 2004 [70]
Federlin and others, 2002 [71]
Idriss and others, 2007 [72]
Szep and others, 2001 [73]
Gallo and others, 2000 [74]
Ghavamnasiri and others, 2007 [75]
Hilton and others, 1997 [76]
Ziskind and others, 1999 [77]
Campos and others, 2005 [78]
Rodrigues and others, 2010 [79]
Uctasi and others, 2002 [80]
Tredwin and others, 2005 [81]
Araujo and others,2006 [82]
Carpena Lopes and Colle, 2009 [83]
Marotta Araujo and others, 1990 [84]
Others restorative variables (cervical margin position, cavity dimensions, matrix systems, etc)
Neiva and others, 1998 [69]
Szep and others, 2001 [73]
Ghavamnasiri and others 2007 [75]
Ziskind and others, 1999 [77]
Campos and others, 2005 [78]
Araujo and others, 2006 [82]
Carpena Lopes and Colle Zanette, 2009 [83]
Marotta Araujo and others, 1990 [84]
Hilton and Ferracane, 1999 [85]
"Sandwich" techniques
Rodrigues and others, 2010 [79]
Tredwin and others 2005 [81]
Malmstrom and others 2002 [86]
Tung and others, 2000 [87]
Frankenberger and others, 2003 [88]
Olmez and others, 2004 [89]
Wibowo and Stockton, 2001 [90]
Attar and others 2004 [91]
Civelek and others 2003 [92]
Fabianelli and others, 2010 [93]
Ziskind and others, 2005 [94]
Sadegui Mostafa, 2009 [95]
Garberoglio and others, 1995 [96]
Aboushala and others, 1996 [97]
Besnault and Attal, 2003 [98]
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An adhesive cavity design (rounded internal geometry) was able to reduce marginal leakage compared to a box-shaped cavity.[84] Beveled margins also had the potential to reduce dentinal leakage, while a delayed finishing protocol (24 hours) had no influence.[85] As for marginal adaptation studies, occlusal loading increased microleakage in enamel.[78]

The microleakage studies reviewed for the aforementioned variables were poorly conclusive.

Sandwich techniques

In enamel margins, a reduction in leakage was observed with increasing thickness of flowable resin composite (FRC), while in dentin, neither the thickness nor the presence of FRC as a gingival increment influenced microleakage.[86] Various adhesive systems (multicomponent, prime and bond, or simplified one component) were combined with FRC liners, but the adhesive type had no impact on dentin and enamel microleakage.[87] However, the presence of the FRC underneath "packable" composite restorations did reduce leakage.[87-89] Conversely, in another trial,[90] the combination FRC/packable restoration showed more microleakage than did a resin-modified glass ionomer (rmGIC)/hybrid restoration. Several other studies[91-93] evaluating the influence of flowable liners observed a comparable, positive effect on microleakage, although, again, other authors[81,94,95] presented conflicting conclusions. When using an autopolymerizing composite as a base underneath a direct light-cured composite restoration, marginal leakage was reduced after four months of humid storage and the consequent water uptake that occurred, compared to the initial status. In this study as well, the adhesive brand was shown to influence microleakage.[96]

In some studies, the placement of a rmGIC liner in Class II open sandwich restorations helped to reduce cervical microleakage in comparison to full composite restorations[97-99] and FRC or autopolymerizing composite liners,[100] while in other studies[79,94,101] it did not have any influence. In one other study,[102] the presence of a rmGIC liner produced more microleakage than was associated with a FRC liner. In a closed sandwich configuration, the rmGIC liner had no effect on microleakage[97] or reduced leakage.[99]

The use of FRC as a liner or base was also evaluated against sandwich techniques using compomer and rmGIC. When comparing those various restorative systems, the sandwich restorations with FRC liner exhibited minimal leakage.[96] However, in similar tests, conflicting conclusions emerged, again with either comparable leakage[90] or increased leakage.[103,104]

Polymerization protocol

The majority of studies comparing different curing protocols or modes (standard, soft-start, step, ramp, pulse, or turbo) did not demonstrate differences in microleakage.[79,105,106] However, when comparing different curing modes, LED curing and Plasma arc curing induced more leakage than did conventional halogen polymerization,[80,107] while with a FRC liner, curing modes (LED vs halogen) had no influence on leakage.[95] Slow, gradual, or delayed light-curing modes reduced leakage compared to standard or modified pulsed and ramp curing.[105,108] The light direction proved not to be an influential factor for microleakage.[86,109]

Different restorative materials and brands

Amalgam used as a base was able to reduce cervical leakage compared to full composite restorations,[13] although such a material combination is not popular anymore. Fiber inserts did reduce leakage at the enamel but not in cervical dentin,[110] and glass fibers were better than polyethylene ones.[111] On the contrary, glass ceramic inserts did not reduce marginal leakage.[112] Finally, restorative hybrids showed less leakage than did packable resin composites, but without eliminating it completely.[113] In fact, no material or brand is able to completely eliminate marginal or cervical leakage at the dentin level.[114] At enamel margins, materials and brands did not have any influence on microleakage.[81,114]

When comparing the performance of various adhesive systems, multicomponent systems (etch and rinse) presented less microleakage than did self-etch systems (one or two components).[115,116] In another study,[117] the comparison between self-etch and multicomponent etch and rinse systems in ambient and extreme temperature and humidity conditions proved to favor the self-etch brand. It was also shown[118] that a double adhesive layer was an effective method to reduce leakage, compared to a single adhesive layer. When comparing restorative composite brands, differences in marginal leakage were observed despite a similar structure and composition.[96] Pursuing the same testing approach, more relevant information was provided when comparing different restorative brands used with the same adhesive.[119] Actually, most of the studies that were reviewed compared different restorative systems (restorative material together with its specific adhesive), and while they observed various levels of leakage at the enamel or cervical dentin,[96,120,121] it is difficult to ascertain whether the adhesive systems, restorative techniques, or materials accounted for the results.

One study[92] compared a conventional hybrid to an ormocer system and observed less leakage with traditional composite technology. The silorane and oxirane restoratives were investigated in regard to their capacity to reduce microleakage. In one study,[122] oxirane produced more leakage than silorane or conventional resin composite. When comparing silorane to a nanohybrid system with either vertical or oblique layering incremental techniques, no leakage was observed with either technique in the silorane group. However, leakage was present in each hybrid composite group but to a reduced extent when using a vertical incremental method.[123]

Comparison of direct and indirect techniques

A comparative leakage study evaluating the performance of direct and indirect composite restorations showed that less leakage occurred in the direct inlay group (one session, chair-side fabrication).[124] In another study, only outer sections showed more leakage in the direct group compared to the inlay technique.[125] A last study confirmed similar resistance to leakage between direct and indirect composite restorations,[126] demonstrating that microleakage studies rarely lead to "conclusive" findings.

Previous sealing of dentin surfaces, followed by a fresh layer of bonding resin application before cementation, was able to reduce leakage compared to a traditional cementation protocol (single application of the adhesive system prior to cementation).[127] When comparing direct techniques with indirect composite and ceramic inlays, the thickness of the cement gap and the divergence of cavity walls proved to be influential factors,[128,129] and the direct technique induced more microleakage.

Marginal leakage of restorations made in vivo

An interesting protocol was applied to evaluate Class II restorations, combining *in vivo* placement and *in vitro* evaluation of microleakage following short-term clinical service and extraction.[130-132] It was shown that none of the techniques investigated was able to fully prevent microleakage *in vivo*[130] at either enamel or cervical dentin[132] and that leakage scores using "classical," mere *in vitro* methodology were poorly predictive of *in vivo* resistance to leakage.[130,132] In one study,[130] the use of a rmGIC proved to have a beneficial effect on cervical microleakage performance. A better resistance to marginal leakage was also found for enamel compared to cervical dentin margins.[131,132] Various matrix systems were tested in this configuration but without any significant influence on leakage.[131]

Conclusion: Microleakage studies

Within the limitations of this study protocol, the most relevant conclusions are that:

- Adhesive cavity design and beveling of margins reduced leakage.
- Halogen curing reduced leakage in comparison to LED and plasma light polymerization.
- Silorane technology induced less leakage than conventional hybrid resin composites.
- Otherwise, the results proved inconclusive in regard to
  - layering or restorative techniques,
  - influence of a low E-modulus liner underneath composite restorations,
  - curing protocol,
  - comparison among composite and adhesive systems and brands, and
  - comparison between direct and indirect techniques.

Conclusions: Marginal leakage methodology

The large majority of published reports did not test microleakage in association with mechanical loading and thermal cycling. It can therefore be considered that in the absence of functional stressing, this protocol mainly and only reveals the influence of the restorative technique (ie, polymerization stresses) and material physicochemical characteristics on the tooth-restoration interface resistance to leakage. In addition, the gap size allowing for die infiltration might be well below the dimension needed for bacterial penetration, which makes the possible clinical relevance of die leakage within ultrasmall margin imperfections unclear. Finally, the results of microleakage tests are only semiquantitative and are therefore less reliable (poor quality of the evidence). Then, regardless of its practical advantage, which in turn led to widespread use of this protocol, the microleakage literature is strongly characterized by limited coherence and conclusiveness (poor consistency of the evidence).

CONCLUSIONS

The first part of this article has reviewed selected literature dealing with the quality and *in vitro* behavior of adhesive Class II restorations using photoelasticity, FEM, and microleakage study protocols.

Photoelasticity has shown higher stresses in large cavities and with the use of light-curing composite, as compared to a chemically curing product. However, it led to conflicting results when comparing layering and bulk-fill techniques. Photoelasticity has several conceptual and methodological drawbacks and has therefore been advantageously replaced by FEM studies.

The validity and crucial role of the FEM protocol was validated by comparing stress levels in similar restorative configurations using natural teeth and strain gauges. This method confirmed the influence on stress of the cavity design and dimensions, layering techniques, and material physical characteristics, such as stiffness. However, cyclic functional loading (fatigue) has not yet been replicated with FEM.

The use of the microleakage protocol allowed only a few hypotheses to be confirmed. Cavity and margin design, light-curing type, and composite structure and technology were the only variables that did have an influence on microleakage. However, when more studies were available, the conclusions regarding other variables proved highly inconsistent and do strongly indicate that the further use of this test method in the future should be strictly limited.

The second part of this review will cover the remaining non-destructive *in vitro* protocols, which include 1) the deformation resistance and fracture resistance to cyclic loading, 2) shrinkage stress and related tooth deformation, 3) bond strength (microtensile, tensile, and shear tests), and 4) marginal and internal adaptation. In addition, an "Evidence Index" will be proposed that aims to classify the different study protocols according to the coherence of their results and their potential clinical relevance, as estimated by their ability to simulate oral biomechanical strains.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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