

Buonocore Memorial Lecture

Placing Dental Composites— A Stressful Experience

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Clinical Relevance

The inevitable generation of stress in dental composites that undergo polymerization shrinkage continues to mandate a precise and careful placement technique to ensure successful clinical outcomes.



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SUMMARY

The setting of dental composites is accompanied by significant polymerization contraction, resulting in the generation of stresses within the material and at the tooth-restoration interface. These stresses can have a deleterious effect on marginal integrity if they exceed the adhesive strength of the restorative, as well as on the

properties of the composite. It has been determined that several factors affect these stresses, including the polymerization rate of the compos-

ite, its formulation, including filler and monomer composition and the constraints imposed by the geometry of the cavity preparation. Many strategies have been developed to reduce the effect of these stresses. Changes in the formulation of the composite have included experimentation with a variety of stress relieving additives, modified catalyst compositions and alternative monomer systems. Modifications to the placement techniques have included the use of incremental curing, altered light activation schemes and resilient liners. This manuscript will review many of the important scientific and clinical issues relating to the generation and quantitation of the stresses produced in dental composites during curing.

WHAT IS THE CLINICAL RELEVANCE OF POLYMERIZATION CONTRACTION STRESS?

There is no proven association between the polymerization contraction behavior of dental composite restorations and their clinical outcomes. But it is true that the primary reason for replacement of dental composites is the diagnosis of secondary caries, and this has not changed in the past 20 years.¹⁻¹² It is also true that the polymerization of these polymer-based materials is accompanied by a volumetric reduction, which may

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vary from as little as 1.5% to as much as 6% for the most common commercial materials, depending upon their specific formulation.¹³ The concern created by this curing shrinkage has made the development of new composite formulations a high priority by dental manufacturers and recently has resulted in materials with volumetric shrinkage approaching 1%.¹⁴ The internal stress generated within the composite during polymerization is considered more important than the actual dimensional change within the cavity preparation, because this stress may linger and/or be readily transferred to any bonded surface. It is the resultant effects of this stress, such as tooth-composite interfacial debonding, cuspal deflection and enamel cracking, that is implicated in the primary reason for failure of these restorations. Whether or not a cause and effect relationship exists, this potential has dictated a fairly precise and careful placement technique by the practitioner in order to optimize clinical outcomes.¹⁵

Thus, concern over the polymerization contraction of dental composite restorations has made placement of these materials a stressful situation for many practitioners and the object of inquiry for many clinical and basic science investigators. Using the keywords “dental composite polymerization stress” in an on-line search (www.pubmed.gov) returned nearly 350 articles from the past 30 years. Several comprehensive review articles have been written on the topic.¹⁵⁻¹⁹ While this article will draw from this extensive body of literature, it will rely heavily on research conducted at Oregon Health & Science University over the past decade to focus on the origins of the internal stresses produced in dental composites during curing, the methods used to measure contraction stress, the physical outcomes resulting from it and the methods attempted to minimize its magnitude and consequences (Figure 1).

WHAT IS THE ORIGIN OF THE INTERNAL STRESS GENERATED IN DENTAL COMPOSITE DURING CURING?

Dental composites are composed of a reinforcing inorganic phase dispersed throughout a relatively rigid,

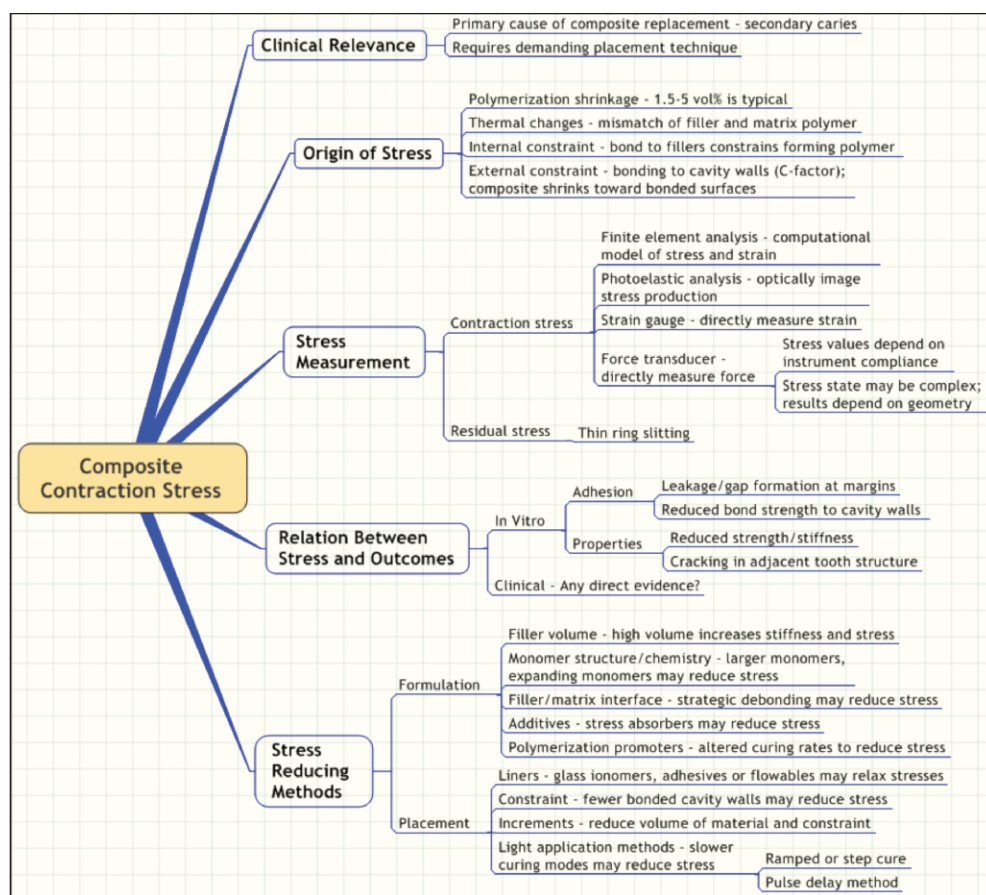


Figure 1. Mindmap showing the organization of the manuscript.

minimally-yielding polymer formed during the curing reaction. Coupling of the two phases typically is mediated by a silane molecule condensed onto the inorganic particles that is capable of covalent bonding to both resin and filler components. The generation of hoop stresses at this interface as the polymer shrinks during curing or cooling has been cited as a contributor to internal stress within the cured composite.²⁰⁻²¹

The polymer of most commercial dental composites is formed from dimethacrylate molecules whose polymerization reaction produces a densely cross-linked, but very heterogeneous polymer network.²²⁻²³ Volumetric contraction is produced by the inherent density gain occurring when molecules previously existing at van der Waal's force distances become linked through shorter covalent bonds. The reduction in free volume within the monomer structure as it transforms to a more densely packed polymer contributes to the overall contraction. The extent of this shrinkage is dependent on the volume fraction of the non-shrinking filler,²⁴ the size of the monomers, that is, the concentration of functional methacrylates per monomer²⁵ and the extent of the polymerization reaction.²⁶⁻²⁸

The transformation of the monomer paste to a polymer is accompanied by significant physical changes that affect the final structure of the composite. As polymerization begins, monomers become reactive by virtue of colliding with free radical initiators that transfer energy.²⁹⁻³⁰ These free radical monomers then collide with other monomers, forming covalent bonds between carbon atoms, and they add together like beads on a string to form polymer chains. As the chains grow, they lengthen and interact with one another, causing a significant increase in viscosity within the paste.³¹ Simultaneously, the polymer gains rigidity as the lengthening chains become entangled with one another and bridges of covalently bonded molecules link chains together to form a cross-linked network. The result is a loss of freedom of motion for individual chains as they become trapped within a rapidly stiffening structure, as indicated by the nearly instantaneous increase in stiffness or elastic modulus.³²⁻³³ It is at this point that the composite becomes a predominantly elastic solid, and any additional change in dimension due to polymerization contraction generates stress according to Hooke's law, where stress is equal to the elastic modulus multiplied by the strain. Thus, increases in shrinkage, combined with an increasing elastic modulus, produce increased stress within the composite structure. Investigators have verified, through modeling and experimentation, that the maximum stress rate occurs early in the polymerization reaction in association with this rapid gain in rigidity.³⁴⁻³⁵

There are additional internal constraints within the curing composite that will add to the magnitude of internal stress. The bond between the filler and formation of the polymer network constrains molecular motion, producing stress. The difference in thermal expansion coefficient between the filler and polymer matrix causes stress at the interface during cooling from the elevated temperature produced by the reaction exotherm and heat from the curing light.²⁰ Attempts have been made to quantitate the internal stress condition of the dental composite using a ring slitting approach that is popular in other industries. This method has shown a strong correlation, with contraction stress measured during the polymerization process.³⁶⁻³⁷

Thus, for a composite material that undergoes polymerization contraction, particularly at the rates associated with current dental applications, it is inevitable that residual stresses will exist within the material. It is also inevitable that some of this stress will be transferred to the surrounding bonded interfaces. The magnitude of these predominantly contraction generated stresses becomes the next concern. As mentioned, the composite becomes a rigid material during curing and is therefore frequently modeled as a purely elastic solid.

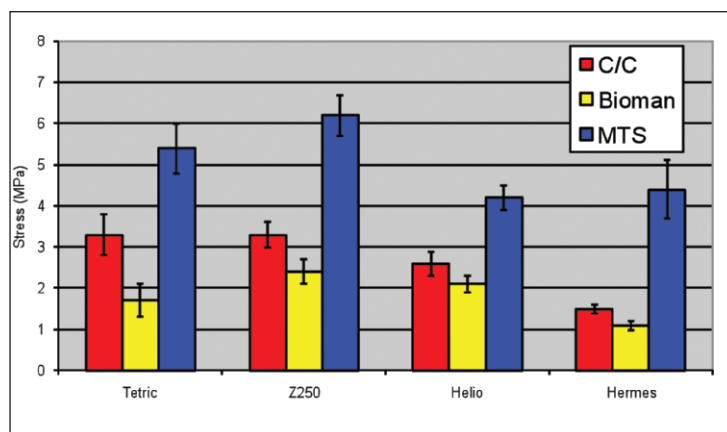


Figure 2. Graph showing contraction stress for four different dental composites cured under similar conditions and constraints in three different testing devices. Higher stresses were recorded in the less compliant, uniaxial MTS system that contained a feedback mechanism to hold the composite thickness constant, than in the more compliant, uniaxial C/C and cantilever Bioman devices that did not rigidly fix the composite thickness.

Based on the assumption of an elastic solid, one can attempt to predict contraction stress for the composite by multiplying its elastic modulus by its shrinkage strain. This calculation predicts a stress ranging from 100-300 MPa for typical commercial dental composites.³⁸⁻³⁹ This stress value is startling and suggests that the forces of contraction surely will lead to interfacial debonding or cohesive fracture of the tooth, composite or both. It therefore becomes critical to be able to measure these contraction stresses.

HOW ARE THE CONTRACTION STRESSES MEASURED?

Contraction stresses in polymerizing dental composites have been measured in various ways over the past 40 years. The most typical method, and the first one employed, measures the generation of force with a transducer (load cell or strain gauge) attached to the polymerizing composite or to a surface to which it is bonded.⁴⁰⁻⁴⁶ Several variations on this basic approach have been used, with perhaps the greatest difference being related to the level of compliance included in the system, purposely or not. Compliance is defined as the change in dimension per unit of force applied or generated, and thus is essentially the inverse of stiffness. Perhaps it is most instructive to associate this parameter with "yielding," as the measuring device and fixtures undergo some amount of deformation that relieves or reduces the forces being created directly by the contracting composite. Any device will be subject to this effect, and the magnitude will be summative over the deformation of the load measuring system, the fixtures, the device frame, the bonded interface, and ultimately, the composite itself. The same can be said for

the clinical situation, where tooth deformation also provides a compliance component during placement of a dental composite restoration. It is relatively obvious that an MOD preparation provides a more compliant structure than does a Class I preparation where the cavity is surrounded by tooth structure with intact marginal ridges.

While it is difficult to control the compliance in all measuring systems, it should at least be quantified. Unfortunately, this parameter often has been overlooked in stress measurement studies. Changes in the compliance within a given test set-up, by altering loading fixtures or geometry, for example, can have profound effects on the measured stresses.⁴⁶⁻⁵¹ Invariably, these studies show measured values of stress as reduced when compliance is increased by changing some parameter within a given testing system. Experiments performed with the same composites, constraint conditions and light curing protocols in the lab at the Oregon Health & Science University have shown differences in measured stresses that depend on the measurement device, and this is explained, in large part, by the different levels of compliance within each system (Figure 2).⁵²

The most obvious difference between stress-measuring methods is in the use of a feedback system that compensates for movement of the testing fixture in response to the contracting composite. When a feedback signal is used to maintain the dimension of the test specimen, that is, inhibit the contraction, the compliance is reduced and the device acts as a "non-yielding," rigid body. Under these conditions, the stress levels are higher than when the system is allowed to deform with the contracting composite. Similarly, the use of more compliant fixtures for supporting the composite, such as acrylic vs glass vs steel, will cause more "yielding" within the system and a lower stress measurement or calculation.^{51,53} In addition, the volume of material used in the test and constraint applied to the curing composite (Configuration factor = bonded surface area/free surface area) will affect the magnitude of the measured stress.⁴¹ Therefore, there is an inherent difficulty in comparing stress values, even for the same composite, when obtained from different test devices or with different test configurations within the same device.

The transducer devices, sometimes referred to as "tensileometers," where the load is produced in a simple tensile or pulling direction, are typically connected to a computer instead of a simple analog recording device. This allows for force data to be sampled at a relatively high frequency in order to capture the rapid forces generated, as the composite almost instantaneously transforms from a paste to a mostly rigid body. Thus, the kinetics of the setting reaction can be indirectly assessed as well with this method (Figure 3).

Other methods that have been used to measure contraction stresses in composites include photoelasticity,⁵⁴⁻⁵⁷ strain gauges attached directly to the composite⁵⁸ or to a substrate upon which the composite is attached⁵⁹⁻⁶⁰ and finite element analysis.^{53,61-62} Each of these methods is capable of distinguishing the factors that affect stress magnitude, such as curing rate, but each must be considered independently, based on the properties of the components of the test device or the assumptions used to create the numerical model. Thus, all of the testing methods discussed are most effective when they are used to determine differences between conditions or materials in systematic experiments, as opposed to predicting absolute magnitudes of the stresses generated for a given composite or curing condition.

While there are significant and explainable differences among the test methods, contraction stresses for typical dental composites reported in the studies cited above have ranged from less than one to more than 15 MPa. In light of the discussed limitations of the test methods, these values still represent a mere fraction of the value predicted for a linear elastic solid undergoing strain of 2% to 5%, which is typical for current dental composites during curing. Choi and others³⁸ suggested that the measured stress generation in composites placed with adhesives of varying thicknesses could be predicted with a numerical model employing a scaling factor equal to 5%, that is, the measured stresses were 5% of the predicted stresses. Therefore, other factors must be contributing to significantly reduce the contraction stresses generated in polymerizing dental composites.

WHY ARE THE MEASURED STRESSES SO MUCH LESS THAN THE PREDICTED?

If the polymerization of dental composite occurs with the composite in a totally unconstrained condition, the internal stresses will be minimized, as even the rapidly stiffening composite has some ability to "flow" away from any free, unconstrained surface. The remaining internal stresses will be due to thermal expansion differences between the filler and matrix and any internally constrained polymerization effects. However, any surface that is impeded from yielding will contribute to the overall stress state, unless the constraint is interrupted. Such is the case when localized debonding occurs within a dental composite restoration. In any case, the greater the external constraint applied to the material during polymerization, for example, by bonding to the walls and floor of the tooth preparation, the greater will be the generation of stress.⁴¹ Conversely, the more "flow" allowed, the less the resultant stress.⁶³ However, the association between constraint and stress generation has proven to be somewhat complex, making it more difficult to make general statements about their effects.^{49,64} In part, this is explained by compliance

of the testing system or the geometry of the tooth preparation. In fact, investigators have suggested that the testing device compliance be adjusted to mimic that of the actual tooth, to maximize the relevance of the test conditions.⁴⁶

Another factor that contributes to the difference between the predicted and measured stress is the fact that the elastic modulus of the composite is changing throughout the curing reaction. Thus, each increment of strain contributes to the next increment of stress to a greater extent than the preceding increment, due to the accompanying stiffness increase. Even if the curing material behaved as a truly elastic solid, one would need to integrate the product of elastic modulus and strain over time to provide a realistic prediction of the overall stress. Therefore, one must be able to account for the dynamic nature of the polymerization reaction and the accompanying physical changes in the composite, in order to predict the stress state at any given time.^{38,65-66} Thus, while the generated stresses may have deleterious effects, as will be discussed next, the overall result may be less than originally anticipated. This would agree with historical data showing the reasonably good success achieved with the clinical placement of dental composites.

WHAT PHYSICAL OUTCOMES ARE ASSOCIATED WITH CONTRACTION STRESSES IN DENTAL COMPOSITE RESTORATIONS?

Tooth deflection, tooth fracture, interfacial debonding, internal debonding, deformation of the contracting composite and deformation of the bonding components or liners have all been cited or investigated as stress-relieving mechanisms that cause measured stresses to be significantly less than those predicted using linear elastic models. Fractures within enamel near margins have been directly related to the curing contraction of dental composites.⁶⁷⁻⁶⁸ These fractures are typically associated with the “white lines” commonly seen around composite cavosurface margins after finishing and prior to the tooth being rehydrated. Leakage and gap formation have been investigated by numerous investigators,⁶⁹⁻⁷⁰ and a correlation between leakage and contraction stress has been verified in several studies.^{38-39,71-72} Numerous studies also have shown reduced bond strength of composite to dentin or enamel when placed in cavities with greater constraint, that is, higher C-factor.^{54,68,73-76} The physical properties, such as elastic modulus and strength, also have been shown to be reduced for composites cured in cavities with greater external constraint,^{74,77} though another study did not show this difference.⁷⁵ While these results may be directly attrib-

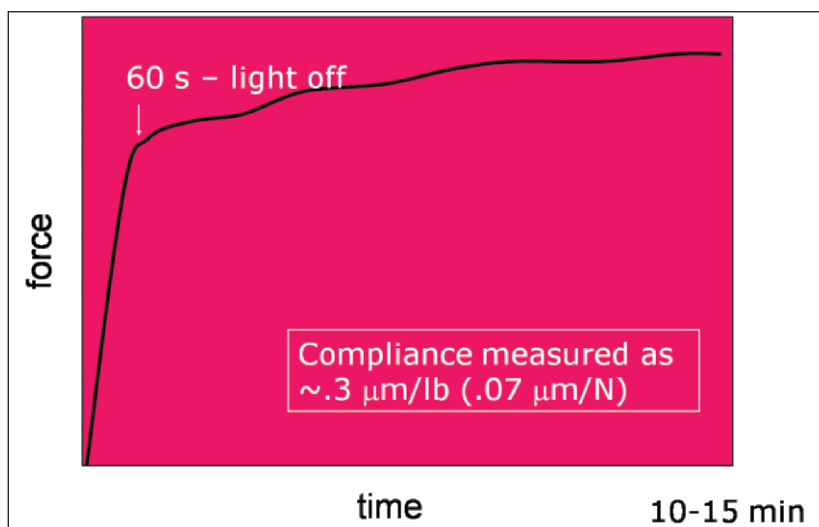


Figure 3. Graph of contraction stress vs time for a light-cured dental composite tested in a uniaxial testing machine. The plot may provide an indirect assessment of curing rate.

utable to the generation of contraction stresses in dental composite restorations, and they provide a rationale for closely following a structured placement technique to minimize their effects, no direct clinical evidence currently exists to support a cause and effect relationship between contraction stress and clinical failure or longevity for these materials.

WHAT METHODS ARE AVAILABLE, OR HAVE BEEN PROPOSED, TO REDUCE STRESS AND ITS EFFECTS?

The formulation of a dental composite affects the magnitude of the stress generated. Studies have shown a correlation between filler content and stress for a variety of commercial products, and this has been explained by the direct relationship between filler volume fraction and elastic modulus.⁷⁸ This relationship is interesting, because one may have assumed that, as the filler content was increased, the stress would be reduced, because there was less monomer available to undergo polymerization shrinkage. But this serves to emphasize the complexity of the problem, as each factor contributes to the final outcome. The strong relationship between filler content and stress would suggest that the elastic modulus is more dominant in determining the stress than shrinkage, and this concept has been supported by Feng and Suh.⁵⁹⁻⁶⁰ However, others have suggested that the curing rate may be most influential in determining stress. In this study, where a direct correlation between elastic modulus and contraction stress was shown, a self-curing composite, having similar filler content than other light cured composites, generated significantly lower stress, presumably due to its slower curing reaction.⁷⁸ This reduced stress for comparable self-cure composites was introduced many years ago⁷⁹ and has been verified by others. The issue of

curing rate may also be related to the acquisition of stiffness and the corresponding reduction in molecular motion allowable for stress relaxation,⁸⁰ and thus, the rate of cure and elastic modulus are inextricably linked.

The type of monomer and its structure also will affect stress generation. Use of larger monomers will reduce the total number of molecules needing to be converted in order to produce the hardened polymer, thus reducing shrinkage.²⁵ Conversely, monomers with enhanced molecular mobility during curing may allow the reaction to proceed to a greater extent, leading to the generation of higher stresses.⁸¹ The inclusion of alternative types of monomers, such as those involved in ring opening polymerization reactions, may also lead to reduced curing shrinkage and stress.^{14,18,82} The volume expansion produced by the opening of a ring can partially offset the curing contraction produced by the simultaneous formation of a covalent bond and a reduction in space between adjacent molecules. A new dental composite has recently been commercialized, based on this concept.

Another idea proposed to reduce composite contraction stress was to incorporate specific stress relieving additives into the composites. The addition of surface treated, semi-deformable, high density polyethylene beads reduced stress generation in composites, but it also reduced mechanical properties.⁸³ Again, it is likely that stress reduction was due to the reduced elastic modulus of the material. The addition of non-bonded spherical silica nanoparticles (fillers containing no silane coating or a non-functional silane coupling agent devoid of polymerizable groups) to both "microfill" and "hybrid" composites have been shown to significantly reduce stress.⁸⁴⁻⁸⁵ The basic concept behind this approach was to reduce internal stress production by providing minimally-adherent particles with a high surface area of reduced-constraint for the polymerizing monomers. The mechanical properties of these materials were not negatively affected, but wear was slightly reduced.

Attempts have been made to slow the curing reaction by altering the concentration of polymerization promoting molecules or by increasing the concentration of inhibitor added to provide adequate shelf-life.²⁷ An order of magnitude increase in the quantity of inhibitor molecules was capable of significantly reducing curing stress without reducing the overall degree of conversion. The effect of this increase in inhibitor on mechanical properties was not evaluated. Another approach has been to incorporate different photosensitizer molecules or a combination of photosensitizers of different reactivity to slow the curing rate. One study showed that polymerization rate could be reduced without negatively affecting degree of conversion when camphorquinone, the most typical photosensitizer used in den-

tal composites, and phenyl propanedione, were used in combination.⁸⁶

In a similar vein, reducing the initial irradiance of light during the curing reaction can significantly slow the curing rate and the rate of stress buildup in composites.^{45,87-88} The rationale behind this approach is to prolong the initial polymerization period, where the material has not acquired sufficient rigidity to inhibit potential stress relieving molecular motions. This critical time has been referred to as the "gel point," or more appropriately, the "gel range," because it is associated with the extent of curing reaction where the polymer has become sufficiently cross-linked to form an insoluble gel. Some investigators consider the reaction rate, even with relatively low irradiance, to be too rapid for this method to be used effectively, because gelation of the polymer occurs after only a small change in overall conversion.^{19,89} While these investigators have shown reduced curing stress with "pulse-delay" techniques (see below), through simultaneous measurement of degree of conversion, they verified that reduced polymerization was the explanation for the reduced stress. They further suggested that previous studies that reported reduced curing stress for composites cured by the "pulse-delay" method were due to reduced conversion, which, though measured to be the same, was not obtained from the same specimens used in the contraction stress test.⁹⁰ However, other investigators have provided evidence that reaction rates can be slowed sufficiently to reduce contraction stress by altering light curing irradiance, while maintaining adequate total curing energy and achieving a high degree of conversion.⁹¹ It is perhaps not surprising that many studies fail to show reduced stress with ramped, exponential or stepped curing methods.⁹² It is likely that the initial irradiance was relatively high, and the rate of cure was still very rapid, surpassing the ability of the polymer to relax the stress buildup through molecular motions.

WHAT CAN THE CLINICIAN DO TO MINIMIZE THE EFFECT OF CONTRACTION STRESSES IN COMPOSITES?

The use of incremental placement, resilient liners and altered light application methods to reduce curing speed have all been suggested as ways the clinician can practically reduce the effects of curing contraction stresses when placing dental composites. Although these methods have not been clinically proven, there is sound logic to support them.

By placing displacement probes or strain gauges on natural teeth, investigators have quantitated cuspal deflections in teeth as a consequence of polymerization shrinkage of bonded dental composite.^{50,92} The direction of this shrinkage has long been of interest. Investigators have shown evidence for composite material shrinking in the direction of constrained surfaces

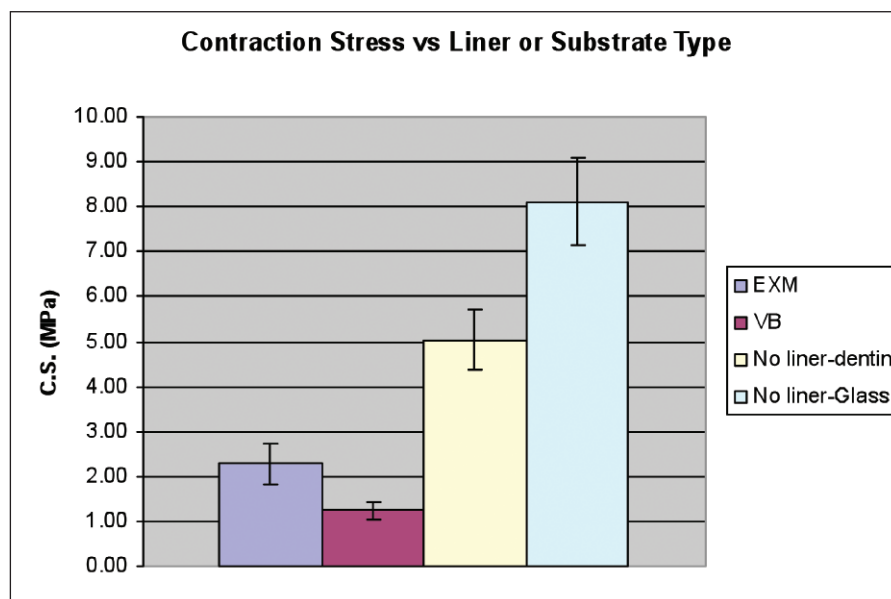


Figure 4. Graph showing the higher contraction stress produced for a dental composite when directly bonded to a dentin surface vs with an intermediate layer of two different resin-modified glass ionomer liner materials. Note also the higher stress measured when bonding the composite to the less compliant glass substrate.

during polymerization.⁹³⁻⁹⁴ In other words, the composite will shrink away from free surfaces and towards any surface to which it is bonded. This outcome implies that the composite will not shrink towards the light source, as has often been conjectured, unless, of course, the light is being shined through a surface to which the composite is bonded. There is one laboratory study that showed evidence for composite curing towards the light under certain conditions when cured within a disk-shaped mold.⁹⁵ However, the complex constraint situation produced by an area of composite flash on the mold makes it difficult to extrapolate these results to the situation produced with a three-dimensional, fully-bonded cavity.

Therefore, if composite shrinkage occurs primarily away from free surfaces, then maximizing the free surface is likely to enhance stress relief by allowing more flow. This, in addition to assuring adequate depth of light penetration, is one of the rationales behind the incremental placement technique. Though the actual placement method may vary from horizontal increments, to vertical increments, to oblique increments, the rationale is the same in that the level of constraint may be reduced with the greater amount of free surface available. There is currently no laboratory or clinical data to provide a definitive answer to the question of what is the most appropriate placement technique. However, based on the current state of the evidence, a technique that uses a large number of small, thin increments, such as the successive cusp buildup technique,⁹⁶ may be expected to produce the least amount of contraction stress.

The use of flexible or deformable liners as stress absorbers has been promoted and evaluated by numerous investigators. Choi and others³⁸ showed that unfilled resin adhesive applied in thick layers under composites could significantly reduce stresses, with the greatest reductions occurring by adding the first one or two additional layers. Glass ionomers have also been proposed as stress reducing liners under composites, whereby stress relief is facilitated by the deformation or internal failure of the weaker ionomer material, thus preserving both the bond to the tooth and the composite.⁹⁷ The author has shown significantly reduced shrinkage stress in a commercial composite when it was applied over a layer of set resin-modified glass ionomer, as opposed to being applied directly onto a dentin surface (presented at the 2006 IADR meeting as a Late Breaking News abstract, Figure 4). Note also in Figure 4 the reduced stress for the composite when it was bonded to dentin as opposed to a glass substrate, again emphasizing the importance of the compliance of the substrate in the magnitude of the measured stress.

Similar efforts to reduce stresses using flowable composites as liners have provided different levels of success, depending upon the characteristics of the particular flowable composite. Some flowable composites have been shown to have high polymerization shrinkage values as a result of their low filler content, resulting in high contraction stresses.⁹⁸ However, these composites may provide stress relief if they have a low stiffness. Evaluations of contraction stress vs elastic modulus verified the effectiveness of certain flowable composites with low elastic modulus to reduce stress, presumably by deforming to absorb some of the composite shrinkage strain.^{94,98-99} Others have shown reduced gap formation in cavities when liners with more rubbery characteristics were placed under composites.¹⁰⁰ It is likely that stress absorbing liners produce a significant reduction in polymerization contraction stress for dental composites in cavity preparations, but the clinical evidence proving enhanced success using this method has not been presented.

Considerable effort has been expended to modify the method of light application to reduce contraction stresses in dental composites. These methods have varied from ramping irradiance from a low to a high level over a period of approximately 10 seconds, to slow the initial reaction (so called "ramped cure"), to the "step cure" method, where a low but constant irradiance is used for

10 seconds, followed by a full cure at a much higher irradiance to produce full conversion, to providing a short dose of low irradiance (3-5 seconds at 100-250 mW/cm²) followed by a waiting period of several minutes before completing curing at high irradiance (so-called "pulse delay"). Some of these methods have been shown to reduce contraction rate, stress or cusp deflection in cavity preparations when measured in the laboratory, but to different extents.^{87,101-103} It is likely that the difference in outcomes is related to the initial irradiance level or ramp-up speed, as well as the delay time when using the "pulse delay" mode, since these will dictate the initial curing rate and may limit any chance for molecular relaxation to reduce stress.^{90,103} It is also likely that the time needed to produce curing with sufficient molecular flow may not be clinically practical by most standards. One study clinically evaluated the effect of a typical, continuous curing protocol vs a soft-start method for Class V composite restorations and saw no difference between the two.¹⁰⁴ Thus, no specific recommendation can be made for a specific technique, despite the fact that the rationale for slowing the polymerization reaction appears to have merit.

SUMMARY

In summary, stresses arise in dental composites during curing, predominantly from polymerization shrinkage. The magnitude of the stress is mediated by the stiffness of the composite, its stress relieving (or "flow") capacity, its curing rate and the constraint applied by bonding to the cavity preparation. These stresses are most often modeled with finite element analysis and photoelasticity and are directly measured with strain gauges or force transducers. In any case, the measured magnitude of stress is dependent upon the assumptions made in the models and the extent of compliance in, and the configuration of, the testing set-up. Verified effects of these stresses include tooth flexure, tooth cracking, interfacial leakage, interfacial debonding and a reduction in mechanical properties of the composite material. The formulation of the composite can be modified to reduce stress, for example, by using larger monomers with fewer functional groups, reducing filler content, incorporating stress absorbing additives, purposely adding non-bonded filler particles or porosity and slowing the kinetics of the curing reaction by altering the concentration of the polymerization promoters or inhibitors. Studies have shown that stresses can be reduced by incremental curing techniques, reduced curing intensities and energies, and altering the mode of curing light application to slow the curing rate. Though no direct clinical evidence exists to support the claim that stresses produced during the polymerization of dental composite restorations lead to failure, the fact that the diagnosis of secondary caries is the primary reason for replacement of dental composites provides sufficient

concern that a demanding, cautious technique for placing these materials remains warranted.

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References

1. Letzel H (1989) Survival rates and reasons for failure of posterior composite restorations in multicentre clinical trial *Journal of Dentistry* **17**(Supplement 1) S10-17.
2. Qvist V, Qvist J & Mjör IA (1990) Placement and longevity of tooth-colored restorations in Denmark *Acta Odontologica Scandinavica* **48**(5) 305-311.
3. Jokstad A, Mjör IA & Qvist V (1994) The age of restorations *in situ* *Acta Odontologica Scandinavica* **52**(4) 234-242.
4. Friedl KH, Hiller KA & Schmalz G (1995) Placement and replacement of composite restorations in Germany *Operative Dentistry* **20**(1) 34-38.
5. Burke FJ, Cheung SW, Mjör IA & Wilson NH (1999) Reasons for placement and replacement of restoration in vocational training practices *Primary Dental Care* **6**(1) 17-20.
6. Mjör IA, Moorhead JE & Dahl JE (2000) Reasons for replacement of restoration in permanent teeth in general dental practice *International Dental Journal* **50**(6) 361-366.
7. Deligeorgi V, Mjör IA & Wilson NH (2001) An overview of reasons for the placement and replacement of restorations *Primary Dental Care* **8**(1) 5-11.
8. Brunthaler A, König F, Lucas T, Sperr W & Schedle A (2003) Longevity of direct resin composite restorations in posterior teeth *Clinical Oral Investigations* **7**(2) 63-70.
9. Manhart J, Chen H, Hamm G & Hickel R (2004) Buonocore Memorial Lecture. Review of the clinical survival of direct and indirect restorations in posterior teeth of the permanent dentition *Operative Dentistry* **29**(5) 481-508.
10. Tyas MJ (2005) Placement and replacement of restorations by selected practitioners *Australian Dental Journal* **50**(2) 81-89.
11. Opdam NJM, Bronkhorst EM, Roeters JM & Loomans BAC (2007) A retrospective clinical study on longevity of posterior composite and amalgam restorations *Dental Materials* **23**(1) 2-8.

12. Bernardo M, Luis H, Martin MD, Leroux BG, Rue T, Leitao J & DeRouen TA (2007) Survival and reasons for failure of amalgam versus composite posterior restorations placed in a randomized clinical trial *Journal of the American Dental Association* **138**(6) 775-783.
13. Kleverlaan CJ & Feilzer AJ (2005) Polymerization shrinkage and contraction stress of dental resin composites *Dental Materials* **21**(12) 1150-1157.
14. Weinmann W, Thalacker C & Guggenberger R (2005) Siloranes in dental composites *Dental Materials* **21**(1) 68-74.
15. Giachetti L, Scaminaci Russo D, Bambi C & Grandini R (2006) A review of polymerization shrinkage stress: Current techniques for posterior direct resin restorations *Journal of Contemporary Dental Practice* **7**(4) 79-88.
16. Carvalho RM, Pereira JC, Yoshiyama M & Pashley DH (1996) A review of polymerization contraction: The influence of stress development versus stress relief *Operative Dentistry* **21**(1) 17-24.
17. Davidson CL & Feilzer AJ (1997) Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives *Journal of Dentistry* **25**(6) 435-440.
18. Braga RR & Ferracane JL (2004) Alternatives in polymerization contraction stress management *Critical Reviews in Oral Biology and Medicine* **15**(3) 176-184.
19. Stansbury JW, Trujillo-Lemon M, Lu H, Ding X, Lin Y & Ge J (2005) Conversion-dependent shrinkage stress and strain in dental resins and composites *Dental Materials* **21**(1) 56-67.
20. Söderholm KJM (1984) Influence of silane treatment and filler fraction on thermal expansion of composite resins *Journal of Dental Research* **63**(11) 1321-1326.
21. Debnath S, Ranade R, Wunder SL, McCool J, Boberick K & Baran G (2004) Interface effects on mechanical properties of particle-reinforced composites *Dental Materials* **20**(7) 677-686.
22. Jancar J, Wang W & DiBenedetto AT (2000) On the heterogeneous structure of thermally cured bis-GMA/TEGDMA resins *Journal of Materials Science: Materials in Medicine* **11**(11) 675-682.
23. Andrzejewska E (2001) Photopolymerization kinetics of multi-functional monomers *Progress in Polymer Science* **26** 605-665.
24. Baroudi K, Saleh AM, Silikas N & Watts D (2007) Shrinkage behavior of flowable resin-composites related to conversion and filler-fraction *Journal of Dentistry* **35**(8) 651-655.
25. Anseth KS, Goodner MD, Reil MA, Kannurpatti AR, Newman SM & Bowman CN (1996) The influence of comonomer composition on dimethacrylate resin properties for dental composites *Journal of Dental Research* **75**(8) 1607-1612.
26. Rueggeberg F & Tamareselv K (1995) Resin cure determination by polymerization shrinkage *Dental Materials* **11**(4) 265-268.
27. Braga RR & Ferracane JL (2002) Contraction stress related to degree of conversion and reaction kinetics *Journal of Dental Research* **81**(2) 114-118.
28. Dewaele M, Truffier-Boutry D, Devaux J & Leloup G (2006) Volume contraction in photocured dental resins: The shrinkage-conversion relationship revisited *Dental Materials* **22**(4) 359-365.
29. Stansbury JW (2000) Curing dental resins and composites by photopolymerization *Journal of Esthetic Dentistry* **12**(6) 300-308.
30. Watts DC (2005) Reaction kinetics and mechanics in photopolymerised networks *Dental Materials* **21**(1) 27-35.
31. Ferracane JL, Moser JB & Greener GH (1981) Rheology of composite restoratives *Journal of Dental Research* **60**(9) 1678-1685.
32. Dauvillier BS, Feilzer AJ, de Gee AJ & Davidson CL (2000) Visco-elastic parameters of dental restorative materials during setting *Journal of Dental Research* **79**(3) 818-823.
33. Sakaguchi RL & Ferracane JL (2001) Effect of light power density on development of elastic modulus of a model light-activated composite during polymerization *Journal of Esthetic and Restorative Dentistry* **13**(2) 121-130.
34. Cunha LG, Alonso RC, Pfeifer CS, Correr-Sobrinho L, Ferracane JL & Sinforeti MA (2007) Modulated photoactivation methods: Influence on contraction stress, degree of conversion and push-out bond strength of composite restoratives *Journal of Dentistry* **35**(4) 318-324.
35. Petrovic LM & Atanackovic TM (2008) A model for shrinkage strain in photo polymerization of dental composites *Dental Materials* **24**(4) 556-560.
36. Park JW & Ferracane JL (2005) Measuring the residual stress in dental composites using a ring slitting method *Dental Materials* **21**(9) 882-889.
37. Park JW & Ferracane JL (2006) Residual stress in composites with the thin-ring-slitting approach *Journal of Dental Research* **85**(10) 945-949.
38. Choi KK, Condon JR & Ferracane JL (2000) The effects of adhesive thickness on polymerization contraction stress of composite *Journal of Dental Research* **79**(3) 812-817.
39. Ferracane JL & Mitchem JC (2003) Relationship between composite contraction stress and leakage in Class V cavities *American Journal of Dentistry* **16**(4) 239-243.
40. Bowen RL (1967) Adhesive bonding of various materials to hard tissues. VI. Forces developing in direct-filling materials during hardening *Journal of the American Dental Association* **74**(3) 439-445.
41. Feilzer AJ, de Gee AJ & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoration *Journal of Dental Research* **66**(11) 1636-1639.
42. Bouschlicher MR, Vargas MA & Boyer DB (1997) Effect of composite type, light intensity, configuration factor and laser polymerization on polymerization contraction forces *American Journal of Dentistry* **10**(2) 88-96.
43. Condon JR & Ferracane JL (1998) Reduction of composite contraction stress through non-bonded microfiller particles *Dental Materials* **14**(4) 256-260.
44. Watts DC, Marouf AS & Al-Hindi AM (2003) Photo-polymerization shrinkage-stress kinetics in resin-composites: Methods development *Dental Materials* **19**(1) 1-11.
45. Sakaguchi RL, Wiltbank BD & Murchison CF (2007) Contraction force rate of polymer composites is linearly correlated with irradiance *Dental Materials* **20**(4) 402-407.
46. Lee SH, Chang J, Ferracane J & Lee IB (2007) Influence of instrument compliance and specimen thickness on the polymerization shrinkage stress measurement of light-cured composites *Dental Materials* **23**(9) 1093-1100.

47. Alster D, Venhoven BA, Feilzer AJ & Davidson CL (1997) Influence of compliance of the substrate materials on polymerization contraction stress in thin resin composite layers *Biomaterials* **18**(4) 337-341.
48. Lu H, Stansbury JW, Dickens SH, Eichmiller FC & Bowman CN (2004) Probing the origins and control of shrinkage stress in dental resin-composites: I. Shrinkage stress characterization technique *Journal of Materials Science: Materials in Medicine* **15**(10) 1097-1103.
49. Witzel MF, Ballester RY, Meira JB, Lima RG & Braga RR (2007) Composite shrinkage stress as a function of specimen dimensions and compliance of the testing system *Dental Materials* **23**(2) 204-210.
50. Meira JB, Braga RR, de Carvalho AC, Rodrigues FP, Xavier TA & Ballester RY (2007) Influence of local factors on composite shrinkage stress development—a finite element analysis *Journal of Adhesive Dentistry* **9**(6) 499-503.
51. Gonçalves F, Pfeifer CS, Meira JB, Ballester RY, Lima RG & Braga RR (2007) Polymerization stress of resin composites as a function of system compliance *Dental Materials* Aug 23 [Epub ahead of print].
52. Musanje L, Sakaguchi RL, Ferracane JL & Murchison CF (2005) Light-source, material and measuring-device effects on contraction stress in composites *Journal of Dental Research* **84**(Special Issue A) Abstract #294.
53. Laughlin GA, Williams JL & Eick D (2002) The influence of system compliance and sample geometry on composite polymerization shrinkage stress *Journal of Biomedical Materials Research* **63**(5) 671-678.
54. Kinomoto Y & Torii M (1998) Photoelastic analysis of polymerization contraction stresses in resin composite restorations *Journal of Dentistry* **26**(2) 165-171.
55. Kinomoto Y, Torii M, Takeshige F & Ebisu S (1999) Comparison of polymerization contraction stresses between self- and light-curing composites *Journal of Dentistry* **27**(5) 383-389.
56. Kinomoto Y, Torii M, Takeshige F & Ebisu S (2003) Polymerization contraction stresses of resin-based composite restorations within beveled cavity preparations of Class I restorations *American Journal of Dentistry* **16**(2) 139-143.
57. Ernst CP, Meyer GR, Klöcker K & Willershausen B (2004) Determination of polymerization shrinkage stress by means of a photoelastic investigation *Dental Materials* **20**(4) 313-321.
58. Sakaguchi RL & Ferracane JL (1998) Stress transfer from polymerization shrinkage of a chemical-cured composite bonded to a pre-cast composite substrate *Dental Materials* **14**(2) 106-111.
59. Feng L & Suh BI (2006) A mechanism on why slower polymerization of a dental composite produces lower contraction stress *Journal of Biomedical Materials Research, Part B Applied Biomaterials* **78B**(1) 63-69.
60. Feng L & Suh BI (2006) The effect of curing modes on polymerization contraction stress of a dual cured composite *Journal of Biomedical Materials Research, Part B Applied Biomaterials* **76B**(1) 196-202.
61. Versluis A & Tantbirojn D (1999) Theoretical considerations of contraction stress *Compendium of Continuing Education in Dentistry* **25**(Supplement) S24-32.
62. Ausiello P, Apicella A & Davidson CL (2002) Effect of adhesive layer properties on stress distribution in composite restorations—a 3D finite element analysis *Dental Materials* **18**(4) 295-303.
63. Feilzer AJ, de Gee AJ & Davidson CL (1990) Quantitative determination of stress reduction by flow in composite restorations *Dental Materials* **6**(3) 167-171.
64. Watts DC & Satterthwaite JD (2008) Axial shrinkage-stress depends upon both c-factor and composite mass *Dental Materials* **24**(1) 1-9.
65. Dauvillier BS, Feilzer AJ, de Gee AJ & Davidson CL (2000) Visco-elastic parameters of dental restorative materials during setting *Journal of Dental Research* **79**(3) 818-823.
66. Dauvillier BS, Aarnts MP & Feilzer AJ (2003) Modeling of the viscoelastic behavior of dental light-activated resin composites during curing *Dental Materials* **19**(4) 277-285.
67. Kanca III J & Suh BI (1999) Pulse activation: Reducing resin-based composite contraction stresses at the enamel cavosurface margins *American Journal of Dentistry* **12**(3) 107-112.
68. Alomari QD, Reinhardt JW & Boyer DB (2001) Effect of liners on cusp deflection and gap formation in composite restorations *Operative Dentistry* **26**(4) 406-411.
69. Uno S & Asmussen E (1991) Marginal adaptation of a restorative resin polymerized at reduced rate *Scandinavian Journal of Dental Research* **99**(5) 440-444.
70. Hannig M & Friedrichs C (2001) Comparative *in vivo* and *in vitro* investigation of interfacial bond variability *Operative Dentistry* **26**(1) 3-11.
71. Calheiros FC, Sadek FT, Braga RR & Cardoso PE (2004) Polymerization contraction stress of low-shrinkage composites and its correlation with microleakage in Class V restorations *Journal of Dentistry* **32**(5) 407-412.
72. Kurokawa R, Finger WJ, Hoffmann M, Endo T, Kanehira M, Komatsu M & Manabe A (2007) Interactions of self-etch adhesives with resin composites *Journal of Dentistry* **35**(12) 923-929.
73. Yoshikawa T, Sano H, Burrow MF, Tagami J & Pashley DH (1999) Effects of dentin depth and cavity configuration on bond strength *Journal of Dental Research* **78**(4) 898-905.
74. Choi KK, Ryu GJ, Choi SM, Lee MJ, Park SJ & Ferracane JL (2004) Effects of cavity configuration on composite restoration *Operative Dentistry* **29**(4) 462-469.
75. Loguercio AD, Reis A & Ballester RY (2004) Polymerization shrinkage; effects of constraint and filling technique in composite restorations *Dental Materials* **20**(3) 236-243.
76. He Z, Shimada Y & Tagami J (2007) The effects of cavity size and incremental technique on micro-tensile bond strength of resin composite in Class I cavities *Dental Materials* **23**(5) 533-538.
77. Nayif MM, Nakajima M, Aksornmuang J, Ikeda M & Tagami J (2008) Effect of adhesion to cavity walls on the mechanical properties of resin composites *Dental Materials* **24**(1) 83-89.
78. Condon JR & Ferracane JL (2000) Assessing the effect of composite formulation on polymerization stress *Journal of the American Dental Association* **131**(4) 497-503.

79. Feilzer AJ, de Gee AJ & Davidson CL (1993) Setting stresses in composites for two different curing modes *Dental Materials* **9**(1) 2-5.
80. Charton C, Colon P & Pla F (2007) Shrinkage stress in light-cured composite resins: Influence of material and photoactivation mode *Dental Materials* **23**(8) 911-920.
81. Charton C, Falk V, Marchal P, Pla F & Colon P (2007) Influence of Tg, viscosity and chemical structure of monomers on shrinkage stress in light-cured dimethacrylate-based dental resins *Dental Materials* **23**(11) 1447-1459.
82. Eick JD, Kotha SP, Chappelow CC, Kilway KV, Giese GJ, Glaros AG & Pinzino CS (2007) Properties of silorane-based dental resins and composites containing a stress-reducing monomer *Dental Materials* **23**(8) 1011-1017.
83. Ferracane JL, Ferracane LL & Braga RR (2003) Effect of admixed high-density polyethylene (HDPE) spheres on contraction stress and properties of experimental composites *Journal of Biomedical Materials Research, Part B Applied Biomaterials* **66**(1) 318-323.
84. Condon JR & Ferracane JL (1998) Reduction of composite contraction stress through non-bonded microfiller particles *Dental Materials* **14**(4) 256-260.
85. Condon JR & Ferracane JL (2002) Reduced polymerization stress through non-bonded nanofiller particles *Biomaterials* **23**(18) 3807-3815.
86. Schneider LF, Pfeifer CS, Consani S, Prah SA & Ferracane JL (2008) Influence of photoinitiator type on the rate of polymerization, degree of conversion, hardness and yellowing of dental resin composites *Dental Materials* Mar 4 [Epub ahead of print].
87. Cunha LG, Alonso RC, Pfeifer CS, Correr-Sobrinho L, Ferracane JL & Sinhoreti MA (2007) Modulated photoactivation methods: Influence on contraction stress, degree of conversion and push-out bond strength of composite restoratives *Journal of Dentistry* **35**(4) 318-324.
88. Cunha LG, Alonso RC, Pfeifer CS, Correr-Sobrinho L, Ferracane JL & Sinhoreti MA (2008) Contraction stress and physical properties development of a resin-based composite irradiated using modulated curing methods at two C-factor levels *Dental Materials* **24**(3) 392-398.
89. Lu H, Stansbury JW & Bowman CN (2004) Towards the elucidation of shrinkage stress development and relaxation in dental composites *Dental Materials* **20**(10) 979-986.
90. Lim B-S, Ferracane JL, Sakaguchi RL & Condon JR (2002) Reduction of polymerization contraction stress for dental composites by two-step light-activation *Dental Materials* **18**(6) 436-444.
91. Neves AD, Discacciati JA, Oréface RL & Yoshida MI (2005) Influence of the power density on the kinetics of photopolymerization and properties of dental composites *Biomedical Materials Research, Part B Applied Biomaterials* **72B**(2) 393-400.
92. Fleming GJP, Cara RR, Palin WM & Burke FJT (2007) Cuspal movement and microleakage in premolar teeth restored with resin-based filling materials cured using a 'soft-start' polymerization protocol *Dental Materials* **23**(5) 637-643.
93. Versluis A, Tantbirojn D & Douglas WH (1998) Do dental composites always shrink toward the light? *Journal of Dental Research* **77**(6) 1435-1445.
94. Cho BH, Dickens SH, Bae JH, Chang CG, Son HH & Um CM (2002) Effect of interfacial bond quality on the direction of polymerization shrinkage flow in resin composite restorations *Operative Dentistry* **27**(3) 297-304.
95. Asmussen E & Peutzfeldt A (1999) Direction of shrinkage of light-curing resin composites *Acta Odontologica Scandinavica* **57**(6) 310-315.
96. Liebenberg WH (1996) Successive cusp build-up: An improved placement technique for posterior direct resin restorations *Journal of the Canadian Dental Association* **62**(6) 501-507.
97. Kemp-Scholte CM & Davidson CL (1990) Complete marginal seal of Class V resin composite restorations effected by increased flexibility *Journal of Dental Research* **69**(6) 1240-1243.
98. Braga RR, Ferracane JL & Hilton TJ (2003) Contraction stress of flowable composites and their efficacy as stress-relieving layers *Journal of the American Dental Association* **134**(6) 721-728.
99. Cunha LG, Alonso RC, Sobrinho LC & Sinhoreti MA (2006) Effect of resin liners and photoactivation methods on the shrinkage stress of a resin composite *Journal of Esthetic and Restorative Dentistry* **18**(1) 29-36.
100. Dewaele M, Asmussen E, Devaux J & Leloup G (2006) Class II restorations: Influence of a liner with rubbery qualities on the occurrence and size of cervical gaps *European Journal of Oral Sciences* **114**(6) 535-541.
101. Hofmann N, Markert T, Hugo B & Klaiber B (2003) Effect of high intensity vs soft-start halogen irradiation on light-cured resin-based composites. Part I. Temperature rise and polymerization shrinkage *American Journal of Dentistry* 421-430. Erratum in *American Journal of Dentistry* 2004 **17**(3) 220.
102. Alomari QD & Mansour YF (2005) Effect of LED curing modes on cusp deflection and hardness of composite restorations *Operative Dentistry* **30**(6) 684-689.
103. Pfeifer CS, Braga RR & Ferracane JL (2006) Pulse-delay curing: Influence of initial irradiance and delay time on shrinkage stress and microhardness of restorative composites *Operative Dentistry* **31**(5) 610-615.
104. Brackett WW, Covey DA & St Germain HA Jr (2002) One-year clinical performance of a self-etching adhesive in Class V resin composites cured by two methods *Operative Dentistry* **27**(3) 218-222.