the Journal of CONTEMPORARY DENTAL PRACTICE
at www.thejcdp.com
Volume 7 Number 4 September 1, 2006

A Review of Polymerization Shrinkage Stress: Current Techniques for Posterior Direct Resin Restorations

Luca Giachetti, MD, DMD; Daniele Scaminaci Russo, DDS;
Claudia Bambi, DDS; Romano Grandini, MD, DMD

Abstract

In general excellent results cannot be guaranteed when using resin-based composites for posterior restorations. This is due to polymerization shrinkage which can still be regarded as the primary negative characteristic of composite resins.

A review of available literature regarding the polymerization process, its flaws, and suggested strategies to avoid shrinkage stress was conducted.

Several factors responsible for the polymerization process may negatively affect the integrity of the tooth-restoration complex. There is no straightforward way of handling adhesive restorative materials that can guarantee the reliability of a restoration. At present, the practitioner has to coexist with the problem of polymerization shrinkage and destructive shrinkage stress. However, evolving improvements associated with resin-based composite materials, dental adhesives, filling, and light curing techniques have improved the predictability of such restorations.

This critical review paper is meant to be a useful contribution to the recognition and understanding of problems related to polymerization shrinkage and to provide clinicians with the opportunity to improve the quality of composite resin restorations.

Keywords: Resin composite, shrinkage, stress, polymerization

Citation: Giachetti L, Scaminaci Russo D, Bambi C, Grandini R. A Review of Polymerization Shrinkage Stress: Current Techniques for Posterior Direct Resin Restorations. J Contemp Dent Pract 2006 September;(7)4:079-088.

Introduction

Composite resins were first introduced in the 1960s as a possible alternative to acrylic resin. However, resin-based composites demonstrated poor wear resistance, polymerization shrinkage, and poor dentin marginal adaptation. They also presented technical challenges in achieving good proximal contact and contour. As a result, their use was limited to class III, IV, and V cavity preparations. In the past ten years the improved performance of composite resins along with the increasing demand for esthetic perfection have encouraged more clinicians to select resin-based composites for posterior restorations as an alternative to amalgam.

However, it is generally accepted resin-based composites are not yet able to guarantee excellent results when used for posterior restorations. This is due to polymerization shrinkage which can still be regarded as the primary negative characteristic of composite resins.

The aim of this paper is to review the effects of polymerization shrinkage on currently used composite resins as well as the methods controlling the development of polymerization shrinkage stress.

Polymerization Shrinkage

Polymerization shrinkage is one of the dental clinician's primary concerns when placing direct resin-based posterior composite restorations. Polymerization of dimethacrylate-based composites is always accompanied by substantial volumetric shrinkage in the range of 2 to 6%.[1,2,3] During polymerization the conversion of monomer molecules into a polymer network results in a closer packing of the molecules leading to bulk contraction.[4,5,6]

In the earliest stage of setting shrinkage is maximal, but fortunately the material is still weak and able to yield. Presumably only chain formation takes place and cross-linking is not yet at full reaction[7] allowing molecules to slip into new positions. At a later stage, although the contraction decreases, the material gains strength and is less able to yield.[7]

Shrinkage Stress

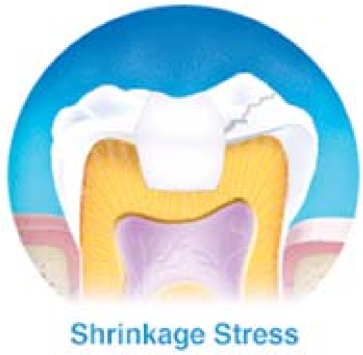
Clinically composite strain is hindered by the confinement of the material bonded to the tooth; as a result, shrinkage manifests itself as stress. It is widely accepted this condition often results in heavily pre-stressed restorations which may have adverse clinical consequences such as the following:[8]

1. Polymerization contraction stress is transferred to the tooth and causes deformation. This tooth deformation may result in enamel fracture, cracked cusps, and cuspal movement.[9,10,11]
2. Polymerization shrinkage stress has the potential to initiate failure of the composite-tooth interface (adhesive failure) if the forces of polymerization contraction exceed dentin bond strength.[12] Such gaps between the resin and cavity walls may cause post-operative sensitivity,[13] micro-leakage, and secondary caries.[14]
3. Stress has the potential to initiate micro-cracking of the restorative material.[15] If the bonding to the cavity walls was strong enough to avoid gap formation during hardening, the stress concentrated inside the composite material would produce micro-cracks before complete setting.[16] However, this never occurs since the

Polymerization Shrinkage

Polymerization Shrinkage

Polymerization Shrinkage



compliance of the surrounding structures sufficiently reduces the setting stress to a level below the cohesive or adhesive strength. The remaining stress (residual stress) is maintained by the total elastic deformation of all materials involved in the tooth's restoration. As a result of this phenomenon, a restored tooth remains under stress even when there is no functional loading on it. This, therefore, implies a greater risk of failure during the tooth's function.[17,18]

4. The shrinkage stress depends on the size of the restoration and, therefore, on the thickness of the cavity wall. The tooth's resistance to polymerization shrinkage diminishes with loss of hard dental tissue. Larger restorations result in lower stress levels in the restoration and tooth-restoration interface but increase stress in the tooth.[18]

Factors Responsible for Polymerization Shrinkage Stress

Filler Content

Composite resins consist of polymer matrix and filler material. Shrinkage is a direct function of the volume fraction of polymer matrix in the composite. The more monomer entities unite into polymer chains and form networks, the higher the composite contraction. On the other hand, the space occupied by filler particles does not participate in the curing contraction. Therefore, the presence of high filler levels is fundamental to reduce shrinkage of the composite during polymerization.[19] Filler content directly influences the mechanical properties and wear resistance of a composite resin.[20,21] Because of its effect on elastic modulus and volumetric shrinkage the amount of filler contained in a resin-based composite is a major factor in terms of polymerization contraction stress development.[22]

Degree of Conversion

There is a direct relationship between degree of conversion and shrinkage.[6,23] For a given composite, a reduction in the final degree of conversion will lead to lower shrinkage and lower contraction stress. However, a low degree of conversion might compromise some of the material's mechanical properties.[24] In contrast, small increases in the degree of conversion will produce substantial increases in stress but will improve the mechanical properties of the material.[25]

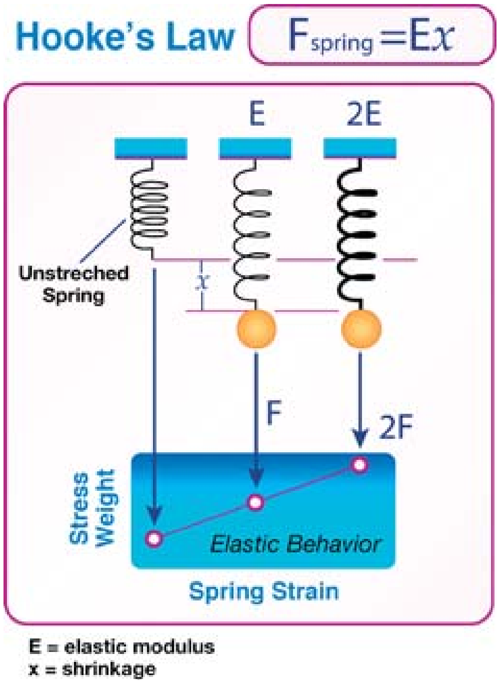
Elastic Modulus

In vitro studies have shown the interfacial stress during the setting shrinkage of a resin composite is positively correlated with the stiffness rate of the setting material known as elastic modulus or Young's modulus.[26] Therefore, at a given shrinkage value, the most rigid material (the material showing the highest elastic modulus) will cause the highest stress. Obviously, the elastic modulus also increases as the polymerization reaction proceeds.[27]

The higher the elastic modulus and polymerization shrinkage of the composite, the higher the contraction stress. Stress is determined by the volumetric shrinkage multiplied by the elastic modulus (Hooke's Law).

Water Sorption

The phenomenon of water sorption of resin composites and their resulting hygroscopic expansion[28,29,30] could compensate for the resin composite shrinkage. Although hygroscopic



expansion may lead to a substantial relaxation of polymerization contraction stress, bonded surfaces are kept from direct contact with water and are restricted in their expansion. As a result, hygroscopic expansion will contribute to the relaxation of shear stress parallel to the adhesive interface.

In contrast to the rather rapid polymerization contraction stress development hygroscopic relief proceeds slowly and might require days. Neither the original contraction stress nor the hygroscopic expansion will be uniform throughout the restoration.

The particular configuration of the restoration will influence the rate and degree of water sorption,[26] thus, generating a gradient from the outer surface to the bulk of the restoration adding new stress.[17]

Despite reducing polymerization shrinkage stress, water sorption causes a series of negative consequences on the composite such as deterioration of mechanical properties and alteration of color stability.

C-factor

There is a relationship between cavity configuration and stress development. Flat surfaces and shallow cavities represent the most favorable conditions for the formation of a durable composite-dentin bond.[31] In these cavities polymerization contraction is restricted to one direction, thus, allowing the composite to flow freely in the early rigid stage (Figure 1A).[7] This condition prevents the contraction forces from producing stress and helps create a strong bond to the cavity walls.[12] When the contraction is hindered in three dimensions, the stress will be less compensated for by flow (Figure 1B).[12]

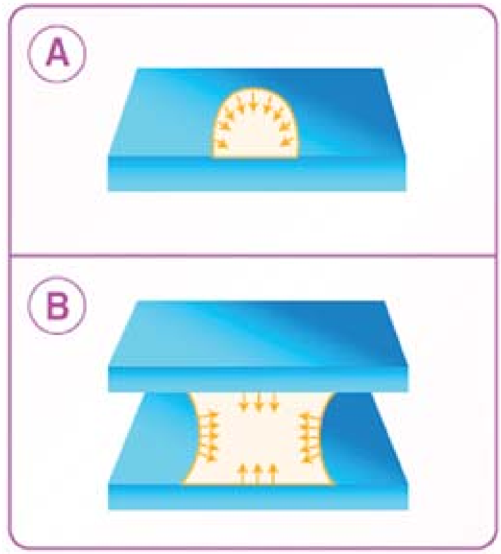


Figure 1. A. schematic representation of resin composite shrinkage vectors on flat surface. **B.** Schematic representation of resin composite shrinkage vectors between two opposite walls.

Feilzer et al.[32] developed the C-factor concept which is the relationship between the ratio of the free and restrained composite surface area of a dental restoration. Based on this overview they performed polymerization stress development experiments on cylindrically shaped specimens, and the results were inclusive of restorations with similar C-ratios (Figure 2). Box-like class I cavities have five bonded walls and only one un-bonded (i.e., surface of composite) surface. The C-factor is 5/1 = 5 if all of the walls have the same surface area. Class V wedge-shaped lesions have lower C-factors, usually between 1.5 and 3, depending on the design. Most clinical restorations have C-values of approximately 1 to 2. Class II and class III restorations may account for these ratios. Values of C≤1 refer to class IV restorations and composite layers applied to flat or shallowly curved surfaces.

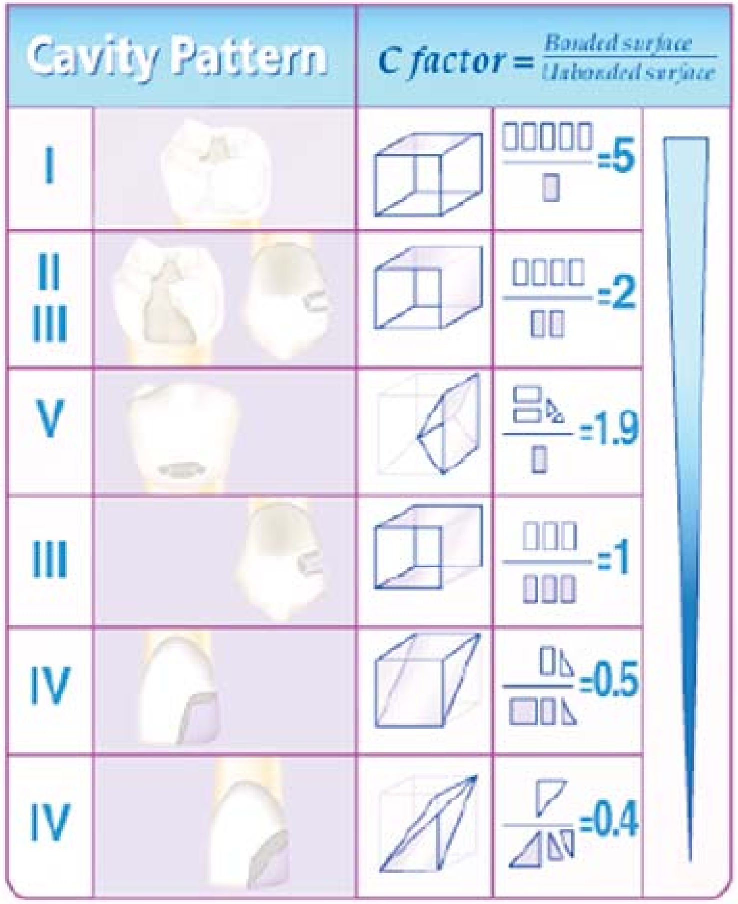


Figure 2. Schematic representations of stress generation in different cavity patterns according to Black's classification.

An increased C-value leads to a decreased flow capacity which causes a higher rate of shrinkage stress development.[32] The less the restoration is bonded to opposing walls, the less shrinkage interference there will be (Figure 3).[33] If two class I cavities have the same volume but a different design, the deeper and narrower cavity will have a higher C-factor than the shallower and larger one.

Management of Shrinkage Stress in Direct Posterior Restorations: Choice of Materials

Flowable Composites

The so-called "flowable composites" were created by retaining the same small particle size of traditional hybrid composites but with a reduced filler content resulting in a reduced viscosity.[34] Low filler content caused some concern regarding inferior mechanical properties and higher polymerization shrinkage when compared to traditional hybrid composites.[3,34,35] However, according to Hooke's law, although the higher polymerization shrinkage of flowable composites could potentially create more stress on interface areas their lower elastic modulus would in turn produce less stress when compared to traditional composites.

It is generally suggested the primary benefit of any low-viscosity composite could be to act as a stress-absorbing layer between the hybrid layer and the shrinkage of the resin composite by partially relieving the polymerization contraction stress. If the walls of the cavity with an unfavorable configuration factor are coated with an elastic layer, the bulk contraction of the restoration can gain some freedom of movement from the adhesive sides. Moreover, such a lining might contribute to a more equal distribution of stress over the adhesive interface. However, the use of

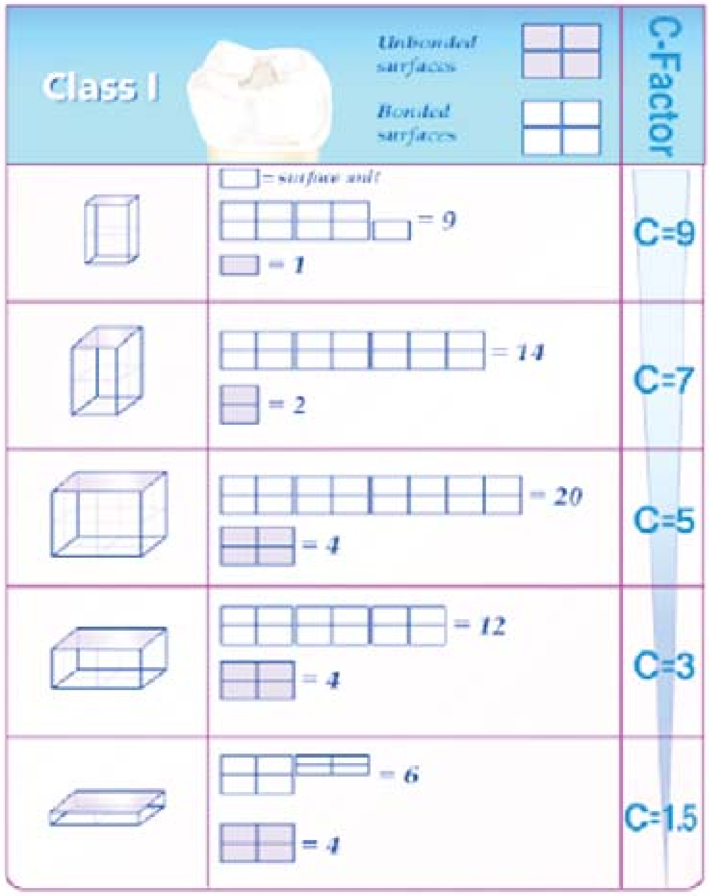


Figure 3. Schematic representations of the effects of cavity configuration on shrinkage stress. Shrinkage stress is influenced by the cavity design.

flowable composites to reduce polymerization shrinkage stress is still being debated and is not widely recommended. It appears the use of a cured thin layer of any composite produces significant stress reduction.[36]

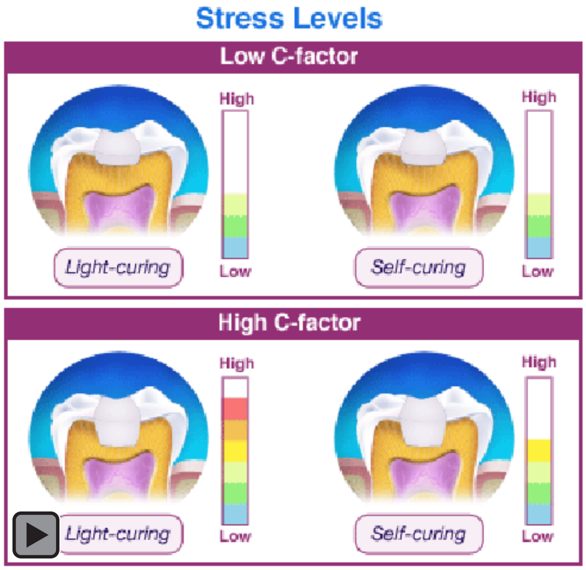
The hybrid layer has a relatively low elastic modulus so it works as a stress absorbing layer. However, it is not as thick as a bonding resin and does not appear to play an important role in relieving stress.[37,38]

Light-curing and Self-curing Composites

Self-curing composites have better marginal adaptation and less microleakage than light-curing ones.[39,40] They develop different polymerization shrinkage stress due to two intrinsic factors: velocity of polymerization and porosity.

The main difference between the magnitudes of the internal stress of self and light-curing composites[41] is the velocity of polymerization of light-curing composite is much higher than self-curing composite. A lower velocity results in a better adaptation of the restoration to the cavity walls.[42] Thus, the velocity of polymerization might affect the flow capacity of the resin composite. As the light-curing composite exists in a gel stage only for a moment, there may not be enough time for the resin composite to flow.

Porosity, which is usually present in self-curing composites, is a result of the mixing procedure and has been shown to decrease shrinkage stress development. This may be due to the inhibiting effect of oxygen in the voids during the setting reaction as well as to an increase in the free surface as a result of the presence



of pores within the bulk of the composite.[43,44] However, porosity may cause degradation of the mechanical properties of composites.[45]

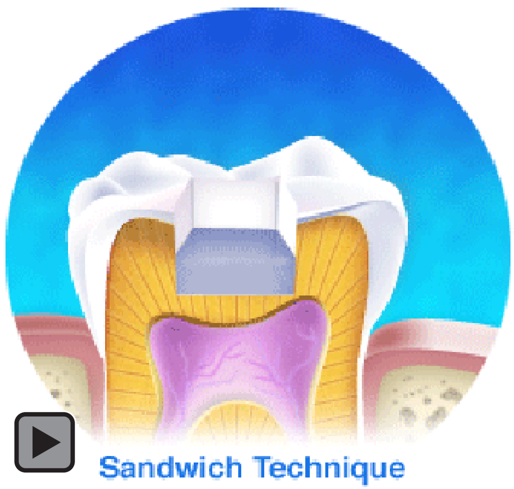
Two additional factors should be taken into account when choosing between a light curing and a self-curing composite: the cavity configuration and the layer thickness. The higher the C-factor, the more evident the difference between the two polymerization processes. In fact when applied on a flat surface or shallow cavity (low C-factor), both composites generate low contraction stress whereas the light curing composites produce a higher stress than the self curing ones when applied to a deep cavity (high C-factor).

Since the intensity of the curing light is highest at the surface and decreases as it penetrates deeper into the composite, the layer thickness has an influence on the degree of conversion of the light-curing composite. When the composite is applied as a single layer, the polymerization of light-curing composites does not induce stress at the bottom of relatively deep cavities due to the low degree of polymerization. On the other hand, stress in self-curing composite would be equally generated within the cavity. In a shallower cavity the maximum polymerization would take place in the light-curing composite throughout the cavity in the same manner as in the self-curing composite, since light would instantly penetrate the composite and there would be a slight reduction of light intensity throughout the material.[41]

Glass-ionomer Cement

The so-called glass ionomer-composite, “sandwich technique,” provides significant clinical advantages. The glass ionomer used as a liner or base offers several advantages as follows:

- Establishes a reliable gap-free chemical bond to composite resins[46]
- Provides anti-cariogenic effects from fluoride release
- Volumetric reduction of composite resin
- Protects the underlying pulp from irritation[47,48]
- Provides a relatively reliable form of adhesion to the dentin with little or no polymerization stress



Therefore, the combined glass ionomer-composite restoration may not only result in improved retention but may also reduce postoperative sensitivity in anterior and posterior composite restorations.

Some authors tested glass ionomer cements in an ‘open sandwich’ technique to seal the cervical cavity margins in class II restorations.

Choice of Restorative Technique

Placement Technique

Restoration placement techniques are widely recognized as a major factor in the modification of shrinkage stress. By using specific restorative techniques stress resulting from constrained shrinkage may be reduced. However, it is not clear which restorative technique should be used to reduce shrinkage stress. Applying the composite in layers instead of using a bulk technique is suggested to reduce shrinkage stress.[49] Three main factors concur to reduce shrinkage stress: use of a small volume of material, a lower cavity configuration factor, and minimal contact with the opposing cavity walls during polymerization.

It is widely accepted incremental filling decreases shrinkage stress as a result of reduced polymerization material volume. Each increment is compensated by the next, and the consequence of polymerization shrinkage is less damaging since only the volume reduction of the last layer can damage the bond surface. Theoretically, if an infinite number of increments were used, the magnitude of polymerization shrinkage would be insignificant.[50] This statement is only partially true since not all polymerization shrinkage occurs immediately after light-activation. Sakaguchi et al.[51] reported immediately following activation only 70–85% of polymerization shrinkage occurred, and after five minutes, this could reach up to 93%.

Moreover, during polymerization shrinkage of the last increment, a considerable strain from the polymerization shrinkage of the first layer can still be under development (leading to a concentration of stress on the adhesive interface). This means the polymerization shrinkage and the consequent stress generated may result in a combined effect of polymerization shrinkage from every increment.[8,52]

The notion each increment can compensate for polymerization shrinkage would only be valid if the increment could be placed in all regions where volume reduction occurs. This only seems to be possible for a deflected surface but not for the volume reduction occurring in the interface and leading to gap formation. On the contrary, the polymerization of additional layers tends to deform the previous increments even more resulting in an increase in the gap width.[53]

Minimal contact with the cavity walls during polymerization is another advantage of the incremental technique. Therefore, there is a lower cavity configuration factor due to the large free surface permitting resin to flow during polymerization.[54] Although all incremental restorative techniques involve a reduction of bonded to unbonded (free) surface ratios, it would be advisable to choose techniques involving the application of the composite to a single dentin surface without touching the opposing cavity walls since shrinkage stress is only produced when composite polymerization is retained in three dimensions.

Several authors currently recommend the use of the incremental technique to reduce contraction stress.[14,54,55,56,57,58] The following are the best known stratification techniques (Figure 4):

- **Facio-lingual Layering (vertical)**
- **Gengivo-occlusal Layering (horizontal)**[59,60,61]
- **Three-site Technique**[62,63] - This is a layering technique associated with the use of a clear matrix and reflective wedges. First, the curing light is directed through the matrix and wedges in the attempt to guide the polymerization vectors toward the gingival margin, thus, preventing any gap formation. Then wedge-shaped composite increments are placed to further prevent distortion of cavity walls and reduce the C-factor. This technique is associated with polymerization first through the cavity walls and then from the occlusal surface in order to direct the vectors of polymerization toward the adhesive surface (indirect polymerization technique).
- **Wedge-shape Layering (oblique)** - In this technique wedge-shaped composite increments are placed and polymerized only from the occlusal surface.[64]
- **Successive Cusp Build-up Technique**[65,66,67]- In this technique the first composite increment is applied to a single dentin surface without contacting the opposing cavity walls, and the restoration is built up by placing a series of wedge-shaped composite increments to minimize the C-factor in 3-D cavity preparations. Each cusp is then built up separately.
- **Bulk Technique** - The bulk technique is recommended by some authors to reduce stress at the cavosurface margins.[8,60]
- **Centripetal Build-up** - This technique was especially developed for class II cavity restorations. An initial vertical composite increment is applied on the cervical margin against the metal matrix. Cavity filling is then completed by horizontally layering

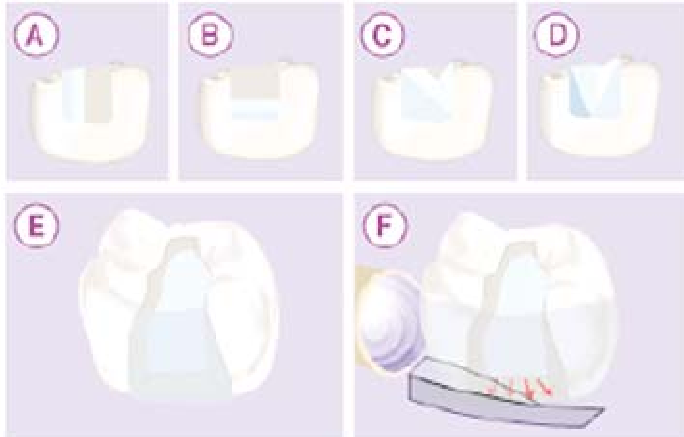


Figure 4. Schematic representations of increment restorative techniques. **A.** Facio-lingual Layering (vertical). **B.** Gengivo-occlusal Layering (horizontal). **C.** Wedge-shape Layering (oblique). **D.** Successive Cusp Build-up Technique. **E.** Centripetal Build-up Technique. **F.** Three-site Technique.

the composite. This technique allows transformation of class II cavities into class I cavities.[68]

Generally greater shrinkage force is generated in the longest dimension of the particular cured volume. This explains the highest values for the wedge increment techniques because the longest dimension of the first increment spans the longest linear distance of any increment; the outer layer of the first increment spans from the junction of the pulpal floor and the wall on one side to the cavosurface margin on the opposite wall. This diagonal transverse dimension is longer than any other dimension in a preparation of this geometry.[52]

A positive effect in terms of lower shrinkage stress due to polymerization in layers can be questioned. This does not imply a layering technique should not be recommended. The main reasons for using the layering technique include easier handling, better modeling of the restoration, and improved material polymerization. In contrast, the bulk light-cured procedure may not be considered clinically relevant since bulk light-curing will result in a low degree of conversion deep inside the restoration.

Polymerization Strategies

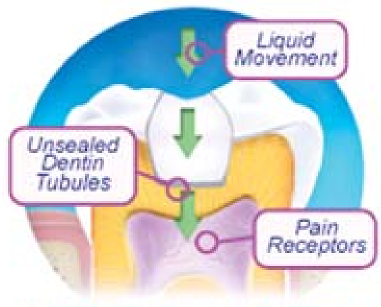
It has been shown high intensity lights may provide higher values for degrees of conversion *(DC)* and physical properties[69,70,71] although they also produce higher contraction strain rates during composite polymerization.[72] A slower curing process may allow stress relaxation to take place during the polymerization process.

A recent approach designed to allow the resin composite some freedom of movement consists of an initially reduced conversion degree of the resin material.

Because the polymerization process is dependent on total light energy rather than light intensity alone, two different approaches can be proposed: the application of a lower intensity light for a longer period time or use of variable intensities over a given period time. An equivalent degree of conversion may be achieved with both techniques.[73]

These techniques initially use low-intensity curing for a short period of time in order to provide sufficient network formation on the composite surface while delaying the gel point in the lower layers until a final high-intensity polymerization is initiated. Excellent marginal sealing and cavity adaptation can be achieved with this method[74,75] since it does not have a detrimental influence on the final conversion rate or on the mechanical properties of the restoration.[76,77,78]

However, some investigators[79,80] did not find any improvement using this soft-start polymerization method. This result may be explained by the different concentrations of photo-initiators. Certain resin-based composites may require shorter exposure time to achieve the same degree of conversion while maintaining the same intensity. The gel point is anticipated even with a soft-start polymerization.



Conclusion

At present, the restorative clinician has to coexist with the problem of resin composite polymerization shrinkage and destructive shrinkage stress. There is no straightforward way of handling adhesive restorative materials that would guarantee the reliability of restorations. This is due to the fact several aspects involved in the polymerization process cannot be controlled and may compromise the integrity of the tooth-restoration complex causing undesirable clinical effects such as post operative sensitivity. Moreover, each clinical case presents unique characteristics.

However, the judicious selection and use of modern dental materials, careful control of polymerization shrinkage, and effective placement techniques can be used to create more predictable and esthetic posterior direct resin composite restorations.

This critical review paper is intended to be a useful contribution to the recognition and understanding of problems related to polymerization shrinkage and to provide clinicians the opportunity to improve the quality of their restorations.

References

1. Bowen RL. Adhesive bonding of various materials to hard tooth tissues–VI. Forces developing in direct-filling materials during hardening. J Am Dent Assoc 1967;74(3):439-45.
2. Walls AW, McCabe JF, Murray JJ. The polymerization contraction of visible-light activated composite resins. J Dent 1988;16(4):177-81.
3. Labella R, Lambrechts P, Van Meerbeek B, Vanherle G. Polymerization shrinkage and elasticity of flowable composites and filled adhesives. Dent Mater 1999;15(2):128-37.
4. Loshaek S, Fox TG. Cross-linked polymers. I. Factors influencing the efficiency of cross-linking in copolymers of methyl methacrylate and glycol methacrylates. J Am Chem Soc, 1953;75:3544-50.
5. Patel MP, Braden M, Davy KW. Polymerization shrinkage of methacrylate esters. Biomaterials, 1987;8:53-6.
6. Venhoven BA, De Gee AJ, Davidson CL. Polymerization contraction and conversion of light-curing bisGMA-based methacrylate resin. Biomaterials, 1993;14:871-5.
7. Davidson CL, de Gee AJ. Relaxation of polymerization contraction stresses by flow in dental composites. J Dent Res 1984;63:146-8.
8. Versluis A, Douglas WH, Cross M, Sakaguchi RL. Does an incremental filling technique reduce polymerization shrinkage stresses? J Dent Res 1996;75:871-8.
9. Jensen ME, Chan DCN. Polymerization shrinkage and microleakage. In: Vanherle G, Smith DC, editors. Posterior composite resin dental restorative materials. Utrecht, The Netherlands: Peter Szulc Publishing Co; 1985:243-62.
10. Suliman AH, Boyer DB, Lakes RS. Polymerization shrinkage of composite resins: comparison with tooth deformation. J Prosthet Dent 1994;71:7-12.
11. Meredith N, Setchell DJ. In vitro measurement of cuspal strain and displacement in composite restored teeth. J Dent 1997;25:331-7.
12. Davidson CL, de Gee AJ, Feilzer A. The competition between the composite-dentin bond strength and the polymerization contraction stress. J Dent Res 1984;63:1396-9.

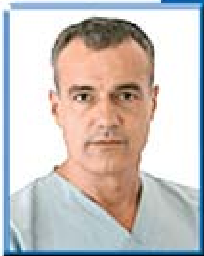
13. Pashley DH. Clinical considerations of microleakage. J Endod 1990;16:70-7.
14. Jensen ME, Chan DCN. Polymerization shrinkage and microleakage. In: Vanherle G, Smith DC, editors. Posterior composite resin dental restorative materials. Utrecht, The Netherlands: Peter Szulc Publishing Co; 1985:243-62.
15. Lai JH, Johnson AE. Measuring polymerization shrinkage of photo-activated restorative materials by a water-filled dilatometer. Dent Mater 1993;9:139-43.
16. Davidson CL, van Zeghbroeck L, Feilzer AJ. Destructive stress in adhesive luting cements. J Dent Res 1991;70:880-2.
17. Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives. J Dent 1997;25:435-40.
18. Versluis A, Tantbirojn D, Pintado MR, DeLong R, Douglas WH. Residual shrinkage stress distributions in molars after composite restoration. Dent Mater 2003;20:554-64.
19. Munksgaard EC, Hansen EK, Kato H. Wall-to-wall polymerization contraction of composite resins versus filler content. Scand J Dent Res 1987;95:526-31.
20. Chung KH, Greener EH. Correlation between degree of conversion, filler concentration and mechanical properties of posterior composite resins. J Oral Rehabil 1990;17:487-94.
21. Condon JR, Ferracane JL. In vitro wear of composite with varied cure, filler level, and filler treatment. J Dent Res 1997;76:1405-11.
22. Condon JR, Ferracane JL. Assessing the effect of composite formulation on polymerization stress. J Am Dent Assoc 2000;131:497-503.
23. Silikas N, Eliades G, Watts DC. Light intensity effects on resin-composite degree of conversion and shrinkage strain. Dent Mater 2000;16:292-6.
24. Ferracane JL, Greener EH. The effect of resin formulation on the degree of conversion and mechanical properties of dental restorative resins. J Biomed Mater Res 1986;20:121-31.
25. Braga RR, Ferracane JL. Contraction stress related to degree of conversion and reaction kinetics. J Dent Res 2002;81:114-8.
26. Feilzer AJ, de Gee AJ, Davidson CL. Relaxation of polymerization contraction shear stress by hygroscopic expansion. J Dent Res 1990;69:36-9.
27. Braem M, Davidson CL, Vanherle G, Van Doren V, Lambrechts P. The relationship between testy methodology and elastic behavior of composites. J Dent Res 1987;66:1036-9.
28. Smith DL, Schoonover IC. Direct filling resins: dimensional changes resulting from polymerization shrinkage and water sorption. J Am Dent Assoc 1953;46:540-4.
29. Bowen RL, Rapson JE, Dickson G. Hardening shrinkage and hygroscopic expansion of composite resins. J Dent Res 1982;61:654-8.
30. Feilzer AJ, De Gee AJ, Davidson CL. Relaxation of polymerization contraction by water swelling. J Dent Res 1988;68:630.
31. Hansen EK. Effect of Scotchbond dependent on cavity cleaning, cavity diameter and cavosurface angle. Scand J Dent Res 1984;92:141-7.
32. Feilzer AJ, De Gee AJ, Davidson CL. Setting stress in composite resin in relation to configuration of the restoration. J Dent Res 1987;66:1636-9.
33. Davidson CL. Resisting the curing contraction with adhesive composites. J Prosthet Dent 1986;55,446-7.
34. Bayne SC, Thompson JY, Swift EJ Jr., Stamatiades P, Wikerson M. A characterization of first-generation flowable composites. JADA 1998;129:567-77.
35. Sabbagh J, Vreven J, Leloup G. Dynamic and static moduli of elasticity of resin-based materials. Dent Mater 2002;18:64-71.
36. Braga RR, Hilton TJ, Ferracane JL. Contraction stress of flowable composite materials and their efficacy as stress-relieving layers. J Am Dent Assoc 2003;134:721-8.
37. Swift EJ Jr, Triolo PT Jr, Barkmeier WW, Bird JL Bounds SJ. Effect of low-viscosity resins on the performance of dental adhesives. Am J Dent 1996;9:100-4.
38. Van Meerbeek B, Willems G, Celis JP, Roos JR, Braem M, Lambrechts P, Vanherle G. Assessment by nano-indentation of the hardness and elasticity of the resin-dentin bonding area. J Dent Res 1993;72:1434-42.

39. Krejci I, Lutz F. Marginal adaptation of class V restorations using different restorative techniques. J Dent 1991; 19:24-32.
40. Itoh K, Yanagawa T, Wakumoto S. Effect of composition and curing type of composite on adaptation to dentin cavity wall. Dent Mater J 1986;5:260-6.
41. Kinomoto Y, Torii M, Takeshige F, Ebisu S. Comparison of polymerization contraction stresses between self- and light-curing composites. J Dent 1999;27:383-9.
42. Kato H. Relationship between the velocity of polymerization and adaptation to dentin cavity wall of light-cured composite. Dent Mater J 1987; 6:32-7.
43. Feilzer AJ, de Gee AJ, Davidson CL. Setting stresses in composites for two different curing modes. Dent Mater 1993;9:2-5.
44. Alster D, Feilzer AJ, De Gee AJ, Mol A, Davidson CL. The dependence of shrinkage stress reduction on porosity concentration in thin resin layers. J Dent Res 1992;71:1619-22.
45. De Gee AJ. Some aspects of vacuum mixing of composite resins and its effect on porosity. Quintessence Int 1979;7:69-74.
46. McLean JW, Powis DR, Prosser HJ, Wilson AD. The use of glass-ionomer cements in bonding composite resins to dentine. Br Dent J 1985;158:410-4.
47. Tobias RS, Browne RM, Plant CG, Ingram DV. Pulpal response to glass ionomer cement. Br Dent J 1978;144:345-50.
48. Suzuki M, Jordan RE. Glass ionomer-composite sandwich tecnique. J Am Dent Assoc 1990;120:55-7.
49. Donly KJ, Jensen ME. Posterior composite polymerization shrinkage in primary teeth: an in vitro comparison of three techniques. Pediatr Dent 1986;8:209-12.
50. Koenigsberg S, Fuks A, Grajower R. The effect of three filling techniques on marginal leakage around class II composite resin restorations in vitro. Quintessence Int 1989;20:117-21.
51. Sakaguchi RL, Peters MC, Nelson SR, Douglas WH, Poort HW. Effects of polymerization contraction in composite restorations. J Dent 1992;20:178-82.
52. Winkler MM, Katona TR, Paydar NH. Finite element stress analysis of three filling techniques for class V light-cured composite restorations. J Dent Res 1996;75:1477-83.
53. Loguercio AD, Reis A, Ballester RY. Polymerization shrinkage: effects of constraint and filling technique in composite restorations. Dent Mater 2004;20:236-43.
54. McCullock AJ, Smith BG. In vitro studies of cuspal movement produced by adhesive restorative materials. Br Dent J 1986;161:405-9.
55. Lutz F, Krejci I, Oldenburg TR. Elimination of polymerization stresses at the margins of posterior composite resin restorations: a new restorative technique. Quintessence Int 1986;17:777-84.
56. Segura A, Donly KJ. In vitro posterior composite polymerization recovery following hygroscopic expansion. J Oral Rehabil 1993;20:495-9.
57. Suliman AA, Boyer DB, Lakes RS. Cusp movement in premolars resulting from composite polymerization shrinkage. Dent Mater 1993;9:6-10.
58. Figueiredo Reis A, Giannini M, Ambrosano GM, Chan DC. The effects of filling techniques and a low-viscosity composite liner on bond strength to class II cavities. J Dent. 2003;31:59-66.
59. Spreafico RC, Gagliani M. Composite resin restorations on posterior teeth. In: Roulet JF, Degrange M. Adhesion: the silent revolution in dentistry. Chicago: Quintessence; 2000:253-76.
60. Lutz F, Krejci I, Barbakow F. Quality and durability of marginal adaptation in bonded composite restorations. Dent Mater 1991;7:107-13.
61. Tjan AH, Bergh BH, Lidner C. Effect of various incremental techniques on the marginal adaptation of class II composite resin restorations. J Prosthet Dent 1992;67:62-6.
62. Lutz F, Krejci I, Luescher B, Oldenburg TR. Improved proximal margin adaptation of class II composite resin restorations by use of light-reflecting wedges. Quintessence Int 1986;17:659-64.
63. Lutz F, Krejci I, Barbakow F. The importance of proximal curing in posterior composite resin restorations. Quintessence Int 1992;23:605-7.
64. Weaver WS, Blank LW, Pelleu GB Jr. A visible light activated resin cured through tooth structure. Gen Dent 1988;36:236-7.
65. Liebenberg WH. Successive cusp build-up: an improved placement technique for posterior direct resin restorations. J Can Dent Assoc 1996;62:501-7.

66. Liebenberg WH. The axial bevel technique: a new technique for extensive posterior resin composite restorations. Quintessence Int 2000;31:231-9.
67. Klaff D. Blending incremental and stratified layering techniques to produce an esthetic posterior composite resin restoration with a predictable prognosis. J Esthet Restor Dent 2001;13:101-13.
68. Bichacho N. The centripetal build-up for composite resin posterior restorations. Pract Periodontics Aesthet Dent 1994; 6:17-23.
69. Rueggeberg FA, Caughman WF, Curtis JW Jr. Effect of light intensity and exposure duration on cure of resin composite. Oper Dent 1994; 19:26-32.
70. Rueggeberg FA, Caughman WF, Curtis JW Jr, Davis HC. Factors affecting cure at depths within light-activated resin composites. Am J Dent 1993;6:91-5.
71. Warren K. An investigation into the microhardness of a light cured composite when cured through varying thicknesses of porcelain. J Oral Rehab 1990;17:327-34.
72. Sakaguchi RL, Berge HX. Effect of light intensity on polymerization contraction of posterior composite. J Dent Res 1997;76:74.
73. Miyazaki M, Oshida Y, Moore BK, Onose H. Effect of light exposure on fracture toughness and flexure strength of light-cured composites. Dent Mater 1996;12:328-32.
74. Uno S, Asmussen E. Marginal adaptation of a restorative resin polymerized at reduced rate. Scand J Dent Res 1991;99:440-4.
75. Mehl A, Hickel R, Kunzelmann KH. Physical properties and gap formation of light-cured composites with and without ‘softstart-polymerization’. J Dent 1997;25:321-30.
76. Sakaguchi RL, Berge HX. Reduced light energy density decreases post-gel contraction while maintaining degree of conversion in composites. J Dent 1998;26:695-700.
77. Feilzer AJ, Dooren LH, de Gee AJ, Davidson CL. Influence of light intensity on polymerization shrinkage and integrity of restoration-cavity interface. Eur J Oral Sci 1995;103:322-6.
78. Unterbrink GL, Muessner R. Influence of light intensity on two restorative systems. J Dent 1995;23:183-9.
79. Friedl KH, Schmalz G, Hiller KA, Markl A. Marginal adaption of Class V restorations with and without “softstart-polymerization”. Oper Dent 2000;25:26-32.
80. Bouschlicher MR, Rueggeberg FA, Boyer DB. Effect of stepped light intensity on polymerization force and conversion in a photoactivated composite. J Esthet Dent 2000;12:23-32.

About the Authors

Luca Giachetti, MD, DMD



Dr. Giachetti is an Assistant Professor and Chair of Dental Materials in the Department of Dentistry of the University of Florence in Florence, Italy. His research interests include dentin bonding agents, dental composites, and esthetic restorative treatment methods. He is a member of the Accademia Italiana Odontoiatria Protesica, the Società Italiana di Odontoiatria Conservatrice, and the Società Italiana di Odontoitria e Chirurgia Maxillo Facciale.

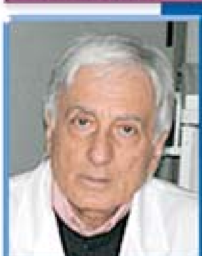
Daniele Scaminaci Russo, DDS

Dr. Scaminaci Russo is a Fellow Researcher in the Department of Dentistry of the University of Florence in Florence, Italy. His research interests include dentin bonding agents and dental composites. He is a member of the Società Italiana di Odontoiatria e Chirurgia Maxillo Facciale and the Società Italiana di Odontoiatria Conservatrice.

Claudia Bambi, DDS

Dr. Bambi is a Fellow Researcher in the Department of Dentistry of the University of Florence in Florence, Italy. Her research interests include dentin bonding agents and dental composites. She is a member of the Società Italiana di Odontoitria e Chirurgia Maxillo Facciale.

Romano Grandini, MD, DMD



Dr. Grandini is a Professor and Chair of Operative Dentistry, Head of the Department of Dentistry of the University of Florence in Florence, Italy. His research interests focus on restorative dentistry. His major organizational memberships include the Academy of Operative Dentistry, Società Italiana di Odontoiatria Conservatrice, Società Italiana di Odontoitria e Chirurgia Maxillo Facciale, and the Academia Italiana di Conservativa.