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Developing a more complete understanding of stresses produced in dental composites during polymerization

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Summary The polymerization of dental composites is accompanied by significant shrinkage and the production of internal stress. This stress has been implicated as a causative factor for marginal discrepancies seen in composite restorations. This paper provides an overview of the origins of these stresses in polymerizing dental composites, a brief description of the methods for measuring them, a discussion of what little is known of the relationship between contraction stress and outcomes, an identification of the materials and placement factors that affect contraction stress, and a description of several strategies proposed to reduce the stresses. The phenomenon of contraction stress development in dental composite restoratives is highly complex, and despite many investigations, remains as a significant clinical concern.

Introduction

The polymerization of dental composites is accompanied by a volumetric contraction, typically on the order of 1.5–5%, which results in the development of internal stresses. The stresses are a product of the non-yielding, or rigid nature of the reinforced cross-linked polymer network formed in the reaction. The stresses have been implicated in the imperfect margins formed around composite restorations, which may lead to a reduced service life. The generation, measurement and characterization of these stresses has been the subject of numerous investigations in the past 35–40 years, beginning with studies by Bowen [1,2] and proliferating after the appearance of work by Davidson et al. [3] and Feilzer et al. [4]. The origin of the stresses, the means for measuring them, the relation between the stresses and clinical outcomes, the clinical factors that affect stress generation, and strategies to reduce them, have all been investigated. The objective of this article is to provide an overview of these topics, placing special emphasis on the studies originating in our laboratory.

Origin of stress in polymerizing dental composite

Dental composites harden by a chemical reaction involving the splitting of carbon–carbon double

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bonds on individual monomer molecules and the formation of carbon–carbon single bonds to form polymer chains. This reaction, which involves the evolution of a significant amount of heat, causes a volume reduction as covalent bonds are created and molecular distances and free volume are reduced.

Several factors contribute to the production of the stresses in resin composites during curing. The shrinkage generated during polymerization occurs simultaneous with the material acquiring rigidity as the polymer chains lengthen, become entangled and cross-link with themselves or neighboring chains. The deformation of this material produces stresses according to Hooke's Law, which describes the linear relationship between the stress and strain in an elastic solid. Since stress is the product of the elastic modulus and the strain, materials with a combination of high volumetric shrinkage and high elastic modulus are expected to generate the highest stresses during polymerization. It is important to emphasize two aspects of this stress development. First, this is a dynamic process where the shrinkage and the elastic modulus both increase with time. Therefore, stress increases in an incremental manner, and cannot be predicted by simply calculating from final values. Second, the polymerizing composite is not a completely elastic solid, and viscous or plastic deformation may reduce stresses during their development.

Other factors contribute to the generated stress as well. The composite heats up during polymerization due to its exothermic nature and the additional energy imparted by the curing unit when light-activation is used. Because there is typically a significant 5–8$\times$ mismatch between the thermal expansion coefficient of the polymer matrix and the reinforcing fillers, thermal stresses are generated at the filler/matrix interface. These thermal stresses occur primarily because the polymer matrix is purposely bonded to the filler surface through a silane coupling agent, thus restricting the molecular motions that might normally occur during thermal shrinkage. Similarly, it has been suggested that covalent bonds and physical molecular interactions occurring between the silane molecules and the polymerizing resin during the reaction also constrain the 'free shrinking' of the polymer, thus causing internal 'hoop' stresses around the fillers [5]. Finally, it is likely that most of the stresses are generated as a result of the entire composite material being constrained during the polymerization reaction through its adherence to the cavity walls. In the absence of bonding to external surfaces, it is likely that residual stress generation from any dimensional change would be substantially lower in composites than is currently measured in cavities of increasing constraint [4].

The internal stresses generated within the composite are transferred to the tooth-composite interface, much as stresses are experienced on every link in a pulled chain. These stresses will appear as tensile forces at the interface, because the composite attempts to shrink toward the bonded surface, but is constrained by the rest of its mass, which is also bonded to an opposing surface. To relieve these stresses, the constrained but contracting polymer matrix will 'flow' from any free surface. It is logical that interfacial stresses will then be reduced for composites cured in cavities with minimal constrained surface area, i.e. class IV type restorations. In addition, localized interfacial failures or weaker bonded areas will provide sites for stress relief. It has been shown that bond strengths of composite to tooth structure vary in magnitude along the interface [6,7]. If the local contraction stresses exceed the local bond strength, stress relieving gaps may form. It has been shown that local debonds will produce gaps that are not always associated with a margin, and therefore are not readily apparent [8]. Other localized failures, such as cracks in the tooth structure [9] or tooth deflection [10], can also occur to partially or fully relieve internal stresses during their generation. It is expected that most of the residual stresses will be relieved as the polymer network absorbs water and time is provided for molecular reorganizations and relaxations.

Methods for measurement of stresses in composites

Numerous methods have been proposed for measuring or estimating the stress produced in dental composites during polymerization contraction. The most common method has been the use of a force transducer to record forces, typically uniaxial, from a composite disk or cylinder [1,3,4,11–16]. Though the premise underlying each of these testing methods is similar, the results for similar materials may vary greatly due to differences in the testing configuration, such as direction of light application and specimen constraint. However, the greatest difference between the test methods is likely the instrument compliance, which may vary from a nearly completely rigid system containing a feedback system for maintaining the specimen dimension [3,4,12,16], to a system with considerable compliance of known [14,15] or unknown [11] magnitude. Contraction stresses measured for