Geometric Factors Affecting Dentin Bonding in Root Canals: A Theoretical Modeling Approach

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Abstract

Cavity configuration factor (C-factor) is the ratio of the bonded surface area in a cavity to the unbonded surface area. In a box-like class I cavity, there may be five times more bonded surface area than the unbonded surface area. During polymerization, the volume of monomers is reduced, which creates sufficient shrinkage stresses to debond the material from dentin, thereby decreasing retention and increasing leakage. The important variables influencing bonding adhesive root-filling materials to canals was examined using a truncated inverted cone model. C-factors in bonded root canals exhibit a negative correlation with sealer thickness. For a 20 mm-long canal prepared with a size 25 file, calculated C-factors ranged from 46 to 23,461 with decreasing sealer thickness (500–1 μm), compared to a C-factor of 32 when the canal was filled only with sealer. As the thickness of the adhesive is reduced, the volummetric shrinkage is reduced, which results in a reduction in shrinkage stress (S-factor). C-factors above 954 calculated with sealer thickness smaller than 25 μm are partially compensated by increases in bonding area and decreases in shrinkage volume. However, the interaction of these two geometrically related factors (C- and S-factors) predicts that bonding of adhesive root-filling materials to root canals is highly unfavorable when compared with indirect intracoronal restorations with a similar resin film thickness.

Key Words

Bonding, root dentin, sealer width, C-factor, relative shrinkage stress

Interest in the application of adhesive dentistry concepts to endodontics (1–6) to create improved apical and coronal seals have been stimulated by the introduction of methacrylate resin-based sealers and dentin adhesives for endodontic use. Some of these materials (EndoRez, Ultradent Products, South Jordan, UT; Fiberfill primers/sealers, Pentron Clinical Technologies, Wallingford, CT) are designed for use with gutta-percha in a single-cone technique (7–11). Others, such as Epiphany (Pentron), Real Seal (SybronEndo, Orange, CA), SimpliFill (LightSpeed, San Antonio, TX), and Next (Heraeus-Kulzer, Armonk, NY), are designed for bonding simultaneously to intraradicular dentin and to Resilon (Resilon Research LLC, Madison, CT), a dimethacrylate/polycaprolactone-containing root filling material using cold lateral or warm vertical compaction techniques (12–15).

Shrinkage stresses associated with polymerization of methacrylate-based resins are higher in low-filled, lower viscosity resin cements, and root canal sealers than highly filled resin composites (16–18). A major problem associated with endodontic bonding is the lack of relief of shrinkage stresses created in deep, narrow canals (19–21). Stress relief by resin flow is dependent upon cavity geometry and resin film thickness (22–24). In a class I box-like cavity, there are five times more bonded surface area than unbonded surface area. The ratio of the bonded to the unbonded surface area is called the configuration factor or C-factor. During polymerization, the unbonded surface can move and flow, thereby relieving shrinkage stresses. However, as the unbonded surface area becomes small, as in a long narrow root canal, there is insufficient stress relief by flow and a high probability than one or more bonded areas will pull off or debond. During the era when bonding to root canals was in its infancy, Feilzer et al. (22) opined that bonding to post spaces represents the worst scenario in achieving leak-free interfaces. Using a 150-μm thick cement layer and taking both dentinal and post bonding areas as their basis of calculation, Bouillaguet et al. (25) reported that C-factors in post spaces may exceed 200, compared to values between 1 and 5 in intracoronal restorations. Because root canal lengths are longer and sealer thickness in some endodontic techniques are thinner (26–28) than what may be expected in post spaces, there is a need to evaluate the geometric variables than can affect dentin bonding in root canals, using a similar modeling approach.

Materials and Methods

Theoretical Modeling

Because root canals can be prepared consistently to a continuous taper (29), an inverted truncated cone model was employed (Fig. 1*A*). Like any modeling approach, assumptions have to be made. In this study, substrate compliances (i.e. the change in material volume per unit stress), gelation times (i.e. the time when liquid monomers polymerize enough to form a gel), and rates of polymerization of the resin sealer are assumed to remain constant. C-factors for root canals prepared with 0.06 taper files with apical diameters varying from 0.20 to 0.40 mm, and lengths varying from 10 to 28 mm were computed in a spreadsheet as the ratios of the total bonded areas to the unbonded area for stress relief.

$$\text{C-factor} = \frac{\text{total bonded area (mm}^2\text{)}}{\text{unbonded area (mm}^2\text{)}}$$

Different scenarios were simulated, with these canals either completely filled with a dual-cured resin sealer, or when the canals were filled with different endodontic

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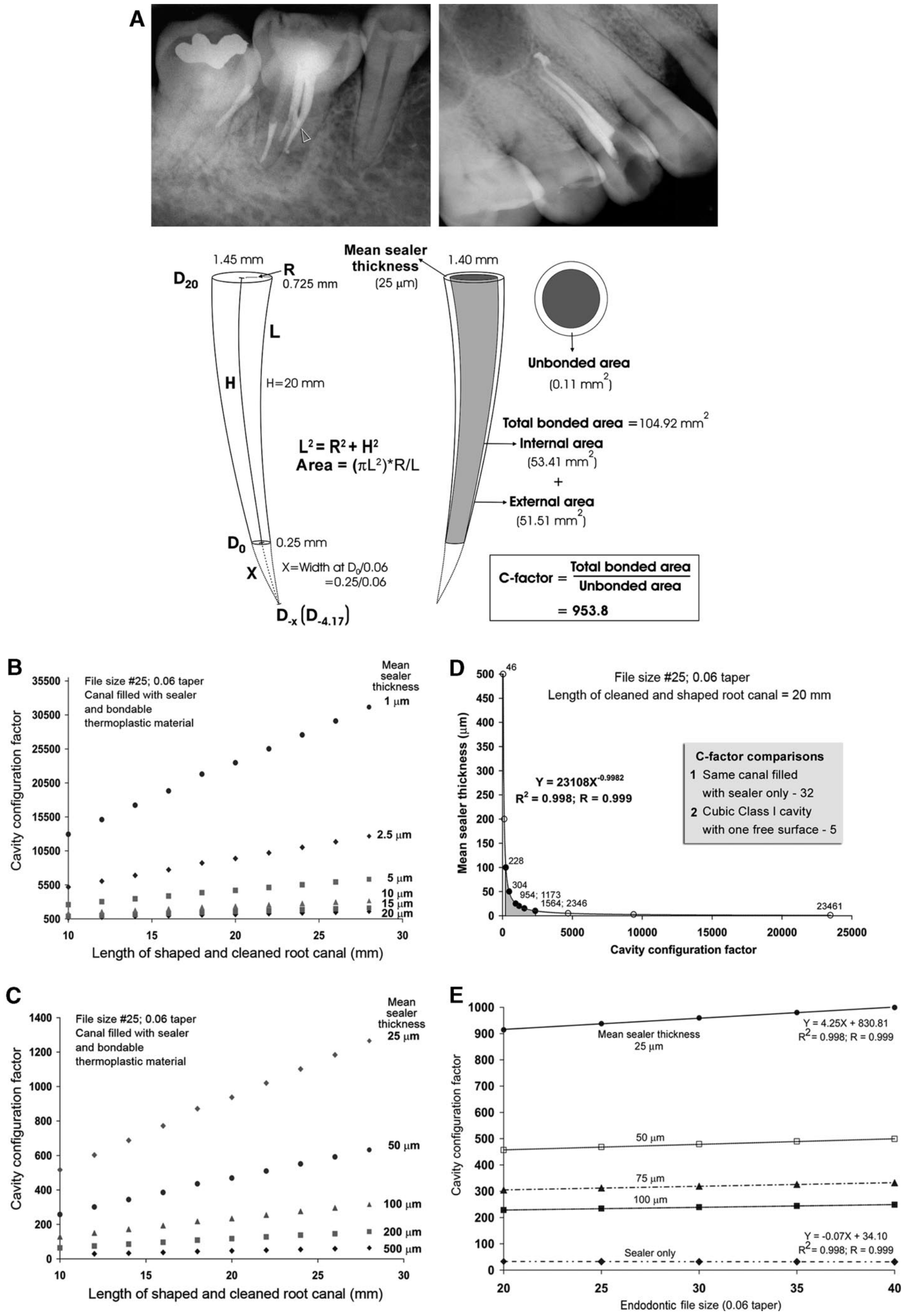

Figure 1. (*A*) A root canal can be modeled as an inverted truncated cone of a continuous taper, as illustrated by the radiographs. The left side of the schematic illustrates a cleaned and shaped root canal prepared to size 25, and 0.06 taper that was bonded with a dentin adhesive and filled with resin cement only. The surface area of the truncated cone was estimated by extending it downward to a point, to first calculate the surface area of the extended cone, and then subtracting the surface area of the short imaginary cone that extended beneath D_0, the working length. The right side of the schematic illustrates the placement of an incompressible, bondable polymerized root filling material of various sizes into the root canal. The peripheral and internal bondable areas in the root canal, as well as the coronal nonbonded area that provides stress relief via resin flow may be mathematically derived from the available data. This allows the cavity configuration factor to be calculated. The calculations of the C-factor of a 20-mm long root canal are illustrated in the box in the schematic. (*B*) C-factors associated with different root canal lengths with mean sealer widths varying from 1 to 20 μm for root canal lengths of 10 to 28 mm. (*C*) C-factors associated with different root canal lengths with mean sealer widths varying from 25 to 500 μm for root canal lengths of 10 to 28 mm. It could be seen that although the C-factor increases with increasing canal length, such an increase is not as important as that contributed by decreasing mean sealer width or thickness. (*D*) The negative correlation between sealer thickness and C-factor for one particular canal length (20 mm) and file size (size 25) is illustrated. A similar negative power correlation exists for all other canal lengths and file sizes. C-factors for sealer thickness ranging from 100 to 10 μm (228–2,346) are highlighted by the black circles and gray zone. They are many times higher than that obtained when the canal is filled with sealer only (C-factor = 32) or that of a bonded cubic intracoronal class I cavity with one free or open surface for resin flow (C-factor = 5). Whereas C-factors in a class I cavity may be reduced by layering techniques, such a strategy is not possible when bonding is performed in root canals. (*E*) Summary of the changes in C-factors that are associated with increasing file sizes from 20 to 40. The increases in C-factors associated with increasing file size are modest when compared with the changes that are associated with reducing the sealer widths. C-factors decrease with increasing file size when a root canal is filled with an adhesive sealer without the use of a bondable root filling material (bottom dashed line in *E*).

materials and techniques that created sealer thickness varying from 1 to 500 μm. An example of deriving the C-factor for a 20-mm long canal prepared to size 25, 0.06 constant taper, and with a mean sealer thickness of 25 μm is shown in Fig. 1*A*. Correlations of C-factors with sealer thickness and file size were performed using regression analyses in Excel (Microsoft, Redmond, WA).

An appraisal of the C-factors that arise from thin resin films was evaluated using an Excel spreadsheet taking into account the decline in geometry-inferred, relative shrinkage stresses that were caused by reductions in net volume, and increases in bonding surface areas with reducing sealer film thickness that is characteristic of bonded root canal fillings. As stress represents force/area, and reduction in shrinkage force is proportional to volume reduction, S-factor was calculated to reflect the changes in the geometrically governed relative shrinkage stress with reducing sealer thickness. In this spreadsheet computation, it was assumed that light-activation of the dual-cured resin sealer from the canal orifice was performed following obturation. This procedure offers the advantage of establishing an immediate coronal seal, but has the disadvantage of blocking the avenue for stress relief by resin flow that may occur when the subsurface light-unreachable, chemically activated sealer is in its pregelation stage.

Experimental Procedures

The Epiphany system was employed to supplement the results of theoretical modeling. Single canals in five human incisors were prepared using a crown-down technique to apical size 25, 1 mm short of the apical foramen using 0.06 taper Profile rotary nickel-titanium instruments (Dentsply Maillefer, Tulsa, OK). Nonstandardized Resilon master cone tips were trimmed and tried-in, with 12-,14-,16-,18-, and 20-mm marks placed on the cone surfaces. The crowns were then severed to create 12- to 20-mm long root canals by making the coronal surfaces flush with the respective marks on the Resilon cones. Irrigation was performed with alternate rinses of 17% EDTA and 3% NaOCl, with the former employed as the final rinse. Epiphany primer was introduced into the root canals with micro-brushes, with the excess blotted with paper points. Epiphany sealer was then placed into the root canals using lentulo spirals, and the Resilon cones were down-packed to the working length using continuous wave warm vertical compaction (System B, SybronEndo, Orange CA) at 150°C. Backfilling with Resilon was performed with the Obtura II (Spartan, Fenton, MO) at 140°C. Excess backfilled materials were removed with heated instruments and the coronal surfaces of the filled segments were light-cured for 40 s to achieve an immediate coronal seal. The severed coronal root surfaces were then covered with a 2-mm thick layer of flowable composite (Æliteflo, Bisco Inc., Schaumburg, IL) using a self-etching primer (Clearfil SE. Bond, Kuraray Medical Inc., Tokyo, Japan) as an adhesive secondary seal.

After storing in distilled water for 24 h, three 2-mm thick cross sections were obtained from the middle portion of the root-filled segments with a slow-speed saw (Isomet, Buehler, Lake Bluff, IL) using copious water cooling. One section from each root was randomly selected for observation of interfacial gaps with a field-emission environmental scanning electron microscope (Philips XL-30 ESEM-FEG; Eindhoven, The Netherlands) at 95% relative humidity and 15 kV. The second section was placed in chloroform for 1 h to dissolve the Resilon before examination with the same microscope for the thickness of the root canal sealer at six locations per section. These sections were etched with 32% phosphoric acid for 10 s to bring the intraradicular dentin into relief before examination. The third section was immersed in an aqueous silver nitrate tracer solution to measure 24 h (30) before dissolution of the Resilon in chloroform and further laboratory processing for transmission electron microscopy (Philips EM208S at 80 kV).

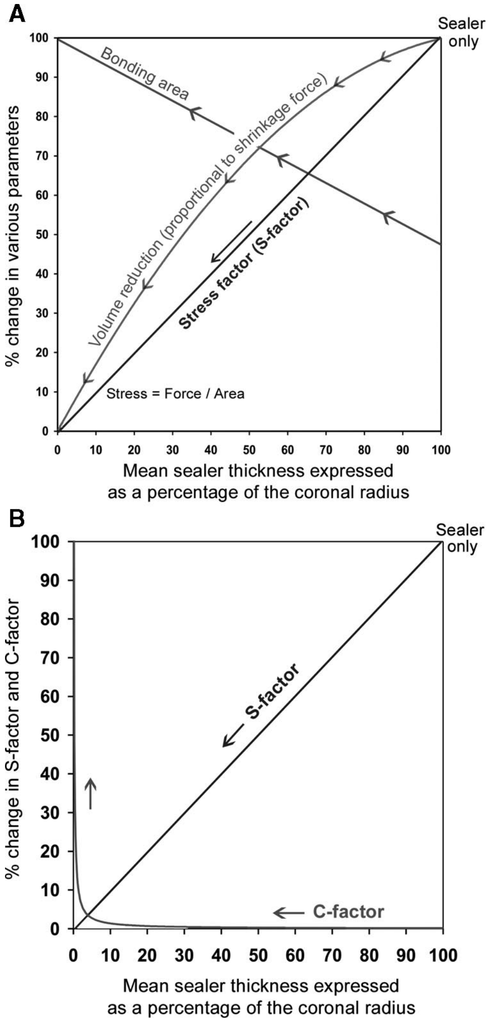

Figure 2. (*A*) The shrinkage force generated during polymerization of a resin sealer is proportional to the net decrease in volume (shrinkage). This shrinkage force is dissipated among the bonded surfaces in the form of "relative" residual (shrinkage) stress. Based on the geometry of an inverted truncated cone, the percentage changes in bonding area, volume-related shrinkage force and stress were calculated at different sealer thickness expressed as a percent of the coronal radius of the canal. (*B*) The dramatic increase in C-factors associated with reducing resin film thickness (*B*) is the dominant variable that determines the polymerization stress that develops when bonding a root filling material with resin sealers.

Results

Figure 1*B* shows variations in calculated C-factors in root canals of varying length from 10 to 30 mm as a function of sealer thickness. Note that C-factors are very high (ca. 500) even in 10 mm long roots. As sealer thickness decreases from 20 to 1 μm, the unbonded flowable amount of sealer decreases, making the C-factor increase rapidly. Thicker sealer reduces C-factors in root canals. Figure 1*C* shows the same relationship but with even thicker sealer widths. With 500 μm thick sealer, the C-factor for 10 mm long roots is about 75. A highly significant negative correlation was noted for the increase in C-factor over the entire range of simulated sealer thickness (Fig. 1*D*). When the root canal was completely filled with adhesive sealer, the C-factor was still 32 compared to a C-factor of 5 for a class I cavity. Increasing the file size incurred only modest increases in C-factors when compared to the increases associated with sealer thickness reductions (Fig. 1*E*).

In Figure 2*A*, the inter-relationships between reductions in the shrinkage force caused by the reduction in sealer volume, and the increases in bonding surface area are plotted relative to the coronal radius of the root canal. This permitted calculation of a single "geometry-inferred shrinkage stress" or S-factor (Fig. 2*A*). When this S-factor was superimposed upon the percentage increase in C-factor (Fig. 2*B*), it was apparent that at clinically relevant sealer thickness, the percentage increase in C-factor overwhelms the percentage decrease in S-factor. Thus, the very high C-factor in root canals is the major obstacle to producing gap-free adhesive fillings in long root canals. The forces of polymerization shrinkage can exceed the resin bond strength to root dentin, permitting debonding on one side of the filling to relieve stress.

Actual resin sealer widths were highly variable within the same tooth and varied from 50 μm (Fig. 3*A*) to incomplete and below 1 μm (Fig. 3*B*). Although gap-free regions could be observed, interfaces with nonartifactual gaps were universally identified in all specimens with different canal lengths using both environmental scanning (Fig. 3*C*) and transmission electron microscopy (Fig. 3*D*), and are thought to be because of polymerization shrinkage stresses exceeding bond strength, causing gap formation during debonding.

Discussion

High C-factors associated with direct intracoronal restorations may be reduced using layering techniques (31). Although this strategy is not applicable for indirect restorations, the general absence of shrinkage stress related postoperative sensitivity in indirect restorations suggests that increases in C-factor cannot solely account for the bonding vulnerability encountered with thin resin layers (32). The previous study of C-factors in post spaces was performed using a single cement

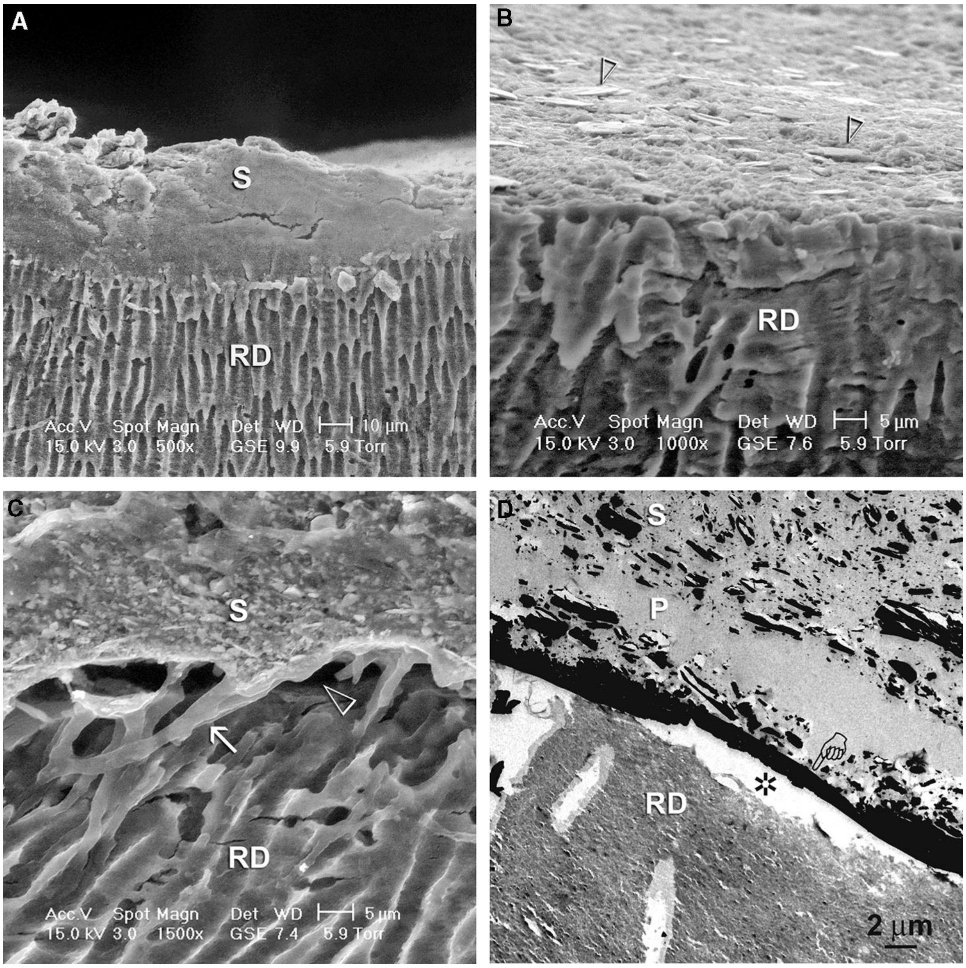

Figure 3. (*A*) An environmental scanning electron micrograph (ESEM) showing the presence of a 20- to 50-mm thick layer of polymerized Epiphany sealer (S) after dissolving the Resilon in chloroform. RD: root dentin. Smearing of the chloroform-treated sealer probably resulted in the inability to identify the fillers, and caused contraction of the sealer that resulted in cracks within the sealer even when the latter was observed at 4°C and 5.9 Torr to create a 95% relative humidity in the microscope. Similar cracks could be seen when bulk polymerized sealer was placed in chloroform (not shown). (*B*) ESEM micrograph from the same section as Fig. 3A, showing the variability in sealer thickness. In this part of the root canal, incomplete plates of resin sealers (open arrowheads), less than 1 μm thick, could be identified from the surface of the root dentin (RD). (*C*) ESEM micrograph showing the presence of an interfacial gap (open arrowhead) despite the creation of resin tags (arrow) by the Epiphany sealer (S) in the root dentin (RD). This is thought to be a result of the high C-factor of the root canal causing sufficient polymerization stress to pull the adhesive sealer off the dentin on one side of the root canal. (*D*) Gaps presumably created by polymerization contraction forces (pointer) could be determined in a transmission electron micrograph by the infiltration of silver nitrate into the interface between the RD and the unfilled Resilon primer (P) and filled sealer (S). As the silver nitrate was reduced to silver before laboratory dehydration, the 2 to 3 μm thick layer of silver deposits represents a true gap that was formed in response to polymerization shrinkage stresses induced by the contraction of the resin sealer. By contrast, the empty space (asterisk) between the RD and the silver layer represents an artifactual space that was created during ultramicrotomy, because there was no bonding between the silver-filled gap and the underlying dentin.

thickness (25) that did not take into consideration the contribution of the other geometric attribute, the S-factor, in partially compensating for the susceptibility of these indirect restorations to interfacial stresses. Comparing the theoretical results of Fig. 1*B*, *C* indicates that a 20 mm long root canal prepared to a size 25 file may have a C-factor varying from a low of 32 with sealer alone, to 46 with a sealer thickness of 500 μm, to a value of 23,461 if the root canal sealer thickness is only 1 μm thick. Thicker sealers can partially compensate for high theoretical C-factors by increasing the unbonded surface area and permitting some stress release by resin flow. For instance, at a sealer thickness of 25 μm in a 20-mm long root canal, the theoretical C-factor of 954 (Fig. 1*C*) could be reduced some because of the linear decrease in S-factor (Fig. 2*A*). Despite the potential reduction in C-factors with a low sealer thickness, it could be seen from the sealer thickness that indirect bonding in long narrow root canals still resulted in exceedingly high C-factors when compared to indirect intracoronal restorations with similar resin film thickness (20, 23, 24, 32).

Although root canals are rarely filled only with resin sealers in contemporary endodontics, this scenario was included to reflect the reductions in C-factor that may occur when canal fins, cul-de-sacs and anastomoses are filled only with sealers (Fig. 1*A*; upper left radiograph, open arrowhead). These bonded spaces are unlikely to provide additional avenues for stress relief if they are filled three-dimensionally, except when voids are present for resin flow (33). Our model did not taken into account the potential contribution of intraradicular dentinal tubules as reservoirs for resin flow that compensate for stress build-ups. As resin tags also adapt to the inner wall of these tubules and create bonded areas peripherally when a dentin adhesive is allowed to autocure before the application of a resin sealer, the availability of dentinal tubules for stress relief is conjectural.

Whereas vulnerability to debonding may be predicted by assessing the geometric attributes of a cavity, the generation of actual shrinkage stresses and how these stresses are ultimately dissipated must rely on other critical parameters such as the amount of volumetric shrinkage of the resin sealer, the elastic moduli of the intraradicular dentin, adhesive, sealer, and root filling material (33), the contribution of air voids within the sealer in stress relief (34), the rate of polymerization and gelation time of the resin sealer (35), and the expansion/contraction involved during thermal plasticization of the root filling material. The influence of these additional parameters can only be evaluated via the use of finite element analysis (FEA). This present work was done simply to estimate the influence of the geometric variables involved in the use of adhesive sealers inside root canals. It provided interesting insight into the advantages and disadvantages of different filling techniques. These calculations are first approximations that set boundary limits for future FEA research.

In view of the high probability for imperfect dentin bonding (i.e. debonding because of polymerization contraction forces exceeding bond strengths) in root canals and the high volumetric shrinkage that is anticipated with low viscosity resinous materials, a slow polymerizing resin sealer would improve the chance for the relief of shrinkage stress via resin flow, because of prolonged gelation time. Indeed, the manufacturer of the Resilon sealer has taken this issue into consideration by creating a sealer that auto-polymerizes in 45 min at room temperature (Dr. Jia Weitao, personal communication). However, the manufacturer's instructions to create an immediate coronal seal via light-curing of the resin sealer would cancel out the benefits derived from a sealer that is designed for very slow auto-curing dynamics (32). For warm vertical compaction techniques, the rate of chemical polymerization of the sealer may also be accelerated by heat application of up to 150°C. Moreover, disruption of the maturing bonds between the self-etching adhesive system and intraradicular dentin may also occur during cold lateral compaction and warm vertical compaction. These additional factors render the concept of total bonding in root canals even more challenging than the bonding of fiber posts. If nonshrinking adhesives are developed, then these high C-factors will not develop during adhesive bonding inside root canals. Such materials are already being developed and may be commercialized within 5 to 10 years. That will truly revolutionize endodontics.

Acknowledgments

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