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Polymerization shrinkage of light-cured dental composite restorations: Basic research and clinical consequences

Polymerisationsschrumpfung lichthärtender dentaler Kompositfüllungen:
Grundlagenforschung und klinische Konsequenzen

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Wohlleb T, **Kaisarly D**, Rösch P, Kunzelmann K-H. 2020. Self-limiting caries excavation with a polymer bur: Adhesive bonding to residual dentin. International Journal of Adhesion and Adhesives. 98(4):102509.

Keßler A, **Kaisarly D**, Hickel R, Kunzelmann KH. 2019. Effect of fiber incorporation on the contraction stress of composite materials. Clin Oral Investig. 23(3):1461-1471.

Kaisarly D, El Gezawi M, Keßler A, Rösch P, Kunzelmann K. 2021. Shrinkage vectors in flowable bulk-fill and conventional composites: Bulk versus incremental application. Clin Oral Investig. 25(3):1127-1139.

Kaisarly D, El Gezawi M, Rösch P and Kunzelmann K-H. 2021. Shrinkage vectors and volumetric shrinkage percentage of differently applied composites. International Journal of Adhesion and Adhesives. 105(3):102793.

Kaisarly D, Meierhofer D, El Gezawi M, Rösch P, Kunzelmann KH. 2021. Effects of flowable liners on the shrinkage vectors of bulk-fill composites. Clin Oral Investig. 25(8):4927-4940.

Kaisarly D, Langenegger R, Litzenburger F, Heck K, El Gezawi M, Rösch P, Kunzelmann KH. 2022. Effects of the application method on the shrinkage vectors and volumetric shrinkage of bulk-fill composites in class-II restorations. Dent Mater. 38(1):79-93.

Content

1 Introduction

1.1 Background

Until today the prevalence of caries is a major global health problem which affects approximately 3.5 billion people (Kazeminia et al. 2020; Watt et al. 2019). Each year, more than 260 million direct composite restorations are placed worldwide (Heintze and Rousson 2012). Advantages of direct composite restorations include excellent esthetics, minimally invasive cavity preparation due to adhesively bonded restorations, their reparability, and relatively low cost. A major disadvantage of composite restorations is the polymerization shrinkage (2 to 6%), which can lead to polymerization shrinkage stresses of 5 to 15 MPa and to debonding from the cavity walls and/or floor (Demarco et al. 2012; Ritter et al. 2019a; Sakaguchi and Powers 2012).

Shrinkage stresses are influenced by the volumetric shrinkage of composites, the modulus of elasticity and the C-factor, which is the ratio of bonded to free surface area (Davidson et al. 1984; Feilzer et al. 1987; Moreira da Silva et al. 2007). Adverse effects of the resulting shrinkage stresses are marginal gaps, marginal discoloration, enamel cracks or fractures, secondary caries, cusp deformities, and/or postoperative hypersensitivity (Feilzer et al. 1987; Kleverlaan and Feilzer 2005; Labella et al. 1999; Tantbirojn et al. 2004).

There are several methods of assessing the polymerization shrinkage of dental composites (Kaisarly and Gezawi 2016). The volumetric shrinkage can be determined according to Archimedes' principle (de Gee et al. 1981; Lee et al. 2005). Early measurements of the linear shrinkage were performed with a linometer (de Gee et al. 1993). The linear shrinkage can be measured according to the "Watts principle" (bonded-disc method) where an uncured composite sample is placed in the center of a ring on which a flexible microscope cover glass is placed and whose deflection is recorded with an LVDT (linear variable differential transformer) probe (Watts and Marouf 2000). Cuspal deflection is an indication of the polymerization shrinkage and can be recorded by an LVDT probe (Moorthy et al. 2012) but also by other methods. Marginal debonding can be quantified both in vivo and in vitro by the marginal gap analysis using the replica technique or by clinical criteria (FDI criteria) (Hickel et al. 2010; Roulet et al. 1989; Roulet et al. 1991). Bond strength tests are indicative of strength of the adhesive interface (Armstrong et al. 2010; Braga et al. 2010). A numerical model of both the tooth and the restoration can be created by the finite element analysis

(FEA), thus, several cavity configurations, different materials and bonding conditions can be investigated without the need for extensive laboratory investigations (Ausiello et al. 2021; Versluis et al. 1998).

Radiological images are increasingly used in medical research and health care (Hill et al. 2001). In the past two decades, micro-computed tomography (micro-CT) has been playing an increasing role in dental research for bone density measurements, determination of mineral content in caries research, caries diagnostics, and FEA (Clementino-Luedemann and Kunzelmann 2006; Lai et al. 2014; Magne 2007; Wagner et al. 2011; Zou et al. 2009).

About a decade ago, the micro-CT has been employed for the first time for non-invasive polymerization shrinkage measurement of dental composites. An uncured composite sample was scanned in the micro-CT, then light-cured and scanned again in the cured state. The volumetric polymerization shrinkage percentage has been calculated by digital image analysis (Sun et al. 2009a; Sun et al. 2009b; Sun and Lin-Gibson 2008; Zeiger et al. 2009).

At about the same time, a method has been developed in Munich to calculate and visualize polymerization shrinkage vectors using micro-CT scans. For this purpose, silanized radiolucent glass beads were embedded in the composite to serve as markers to track the composite deformation upon polymerization. Then the composite filling was scanned in the uncured and cured states in micro-CT. The two micro-CT scans were subjected to the rigid registration that was necessary for overlaying both scans via the outer tooth contours. The glass beads were represented as spheres in the micro-CT scan, and a block-matching algorithm performed sphere registration and segmentation. From the calculated coordinates of the spheres in both scans of a sample, the shrinkage vectors were calculated and quantified. Furthermore, the visualization of the shrinkage vector field allowed qualitative and also localized assessment of the polymerization shrinkage (Chiang et al. 2010).

Other research groups have mixed radiopaque zirconium fillers into a composite to calculate the shrinkage vectors (Cho et al. 2011; Sampaio et al. 2017). However, these could cause radiographic artifacts in the micro-CT scan and interfere with the evaluation. Inherently present fillers of a composite were tracked or air bubbles have been incorporated for the calculation of the shrinkage vectors (Takemura et al. 2014; Van Ende et al. 2015).

1.2 Boundary conditions of dental composite restorations

The polymerization shrinkage and shrinkage stresses of composite restorations are influenced by several factors that can be represented by the boundary conditions of composite restorations. These boundary conditions or influencing factors can be divided into factors related to the cavity, the bonding substrate, the bonding conditions or surface conditioning and the application and curing methods (Figure 1) (Kaisarly 2021). A further category could be considered as a separate entity covering material properties and composition of resin composites such as monomers, matrix blend, filler content and distribution.

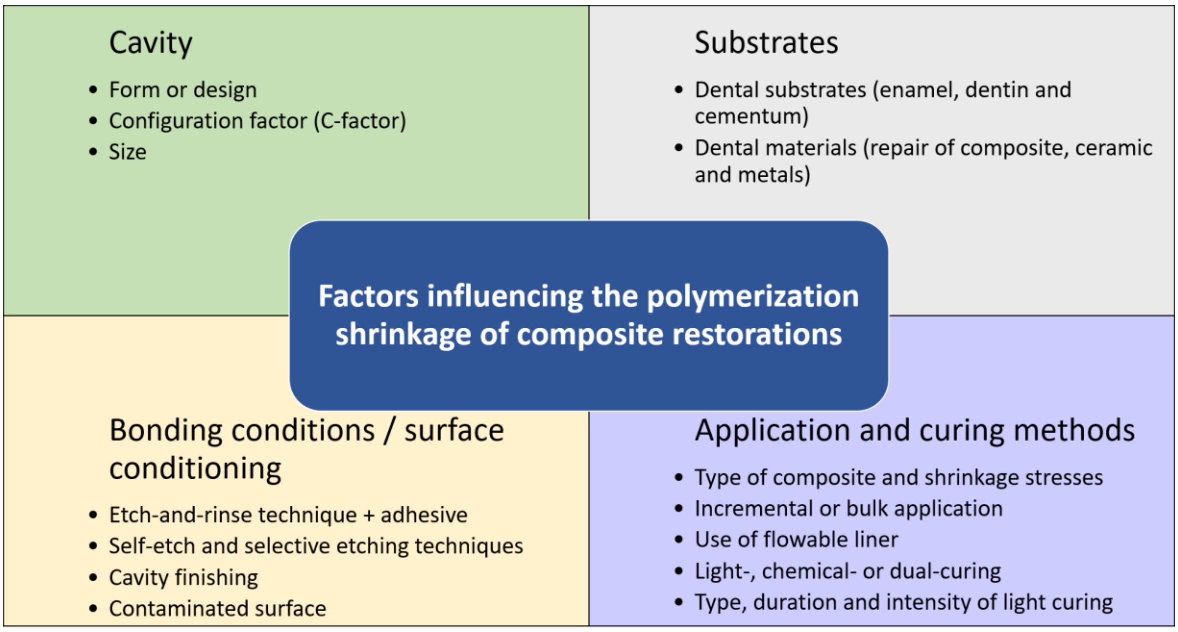

Figure 1 The boundary conditions of composite restorations represent the factors influencing the polymerization shrinkage. The image is modified after Kaisarly 2021 (Kaisarly 2021)

1.3 Research related to the cavity, substrate and bonding conditions

Several studies have investigated the polymerization shrinkage of composite restorations using micro-CT scans (Kaisarly and Gezawi 2016). The focus of research was mainly related to the cavity, the bonding substrate and the bonding conditions (surface conditioning).

Previously, it was assumed that chemically cured composites shrink toward the center and light-cured composites shrink toward the light source. This assumption lead to the development of techniques aiming at guiding the curing light to inaccessible areas (Lutz et al. 1986). The cavity for adhesive restorations should have beveled enamel margins and rounded dentin walls (Porte et al. 1984). The investigation of different cavity configurations showed that the cavity proposed for adhesive restorations showed greatest shrinkage vectors and upward movement away from the cavity floor with potential debonding from the cavity boundaries. In a cavity with diverging walls the shrinkage vectors were directed toward the cavity floor displaying the main movement at the free surface. The shrinkage vectors in a cylindrical cavity without any geometrical variations pointed to the middle horizontal plane of the restoration (Kaisarly et al. 2018a).

Furthermore, the cavity size determined the shrinkage direction. In small cylindrical cavities the shrinkage vectors were directed toward the cavity floor but in larger cylindrical cavities they pointed upward and showed debonding from the cavity floor which was attributed to the increased shrinkage stresses (Van Ende et al. 2015). Even though both cavities have the same C-factor, i.e. the same number of bonded areas, the larger and deeper cavities had a larger bonded area than the smaller cavities. Thus, the greater volume in the larger cavity resulted in greater shrinkage stresses.

The substrates and the corresponding bonding conditions also play an interactive role in the polymerization shrinkage and debonding from cavity boundaries. Enamel and dentin are heterogenous substrates and bonding to enamel is stronger than to dentin (Van Meerbeek et al. 2003). To overcome structural differences of dental substrates basic research has been performed on cavity models made of other substrates. Silanized ceramic cavity models provided the composite restoration with optimal adhesion (bonding conditions or surface conditioning) and resulted in downward movement of composite toward the cavity floor and walls. On the other hand, shrinkage of composite restorations in non-adhesive Teflon cavities displayed shrinkage vectors that pointed to the center of the restoration, as assumed in the chemically cured composites (Kaisarly et al. 2018b).

These insights were tested on dental substrates and experimental cavities with enamel at the cavity bottom were prepared. The enamel floor influenced the shrinkage direction and showed a similar vector field as in the ceramic cavity (Kaisarly et al. 2019). Thus, the shrinkage pattern is influenced by the substrate and not by the type of polymerization initiation. A similar phenomenon was observed in cylindrical cavities with different amounts of enamel at the cavity margins, with shrinkage vectors pointing toward the cavity margin with more enamel (Chiang et al. 2010).

The bonding conditions or surface conditioning play an important role in both the direction and magnitude of polymerization shrinkage. Non-bonded composite restorations showed greater shrinkage vectors and upward movement away from the cavity floor whereas bonded restorations were limited in their movement (Cho et al. 2011). Even the volumetric polymerization shrinkage percentage in bonded and non-bonded restorations resulted in a greater polymerizations shrinkage in the non-bonded groups (Hirata et al. 2015b). The application of a self-etch adhesive versus an etch-and-rinse adhesive also resulted in significant differences, however, the shrinkage vector pattern and direction remained similar whereas the substrate influenced the shrinkage direction (Kaisarly et al. 2019).

1.4 Aim of the study

The aim of this research was to investigate the polymerization shrinkage of dental composite restorations, with the focus on but not limited to bulk-fill composites, and their clinical consequences or implications.

The various aims of this research can be formulated as follows:

1. To study the adaptation of composites under different bonding conditions / surface conditioning.
2. To study how dental substrates affect the polymerization shrinkage.
3. To study the polymerization shrinkage in different cavity configurations: class-I and class-II restorations.
4. To investigate the effects of the application method such as incremental versus bulk application.
5. To investigate the effects of the application of low viscosity composites as flowable liners under hybrid bulk-fill composites (effect of viscosity and elastic modulus).

2 Research and its relevance to the field

2.1 Research related to the bonding conditions (surface conditioning)

The subsequent research is focusing on various aspects concerning the bonding conditions or surface conditioning, which is influenced by the adhesive type and bonding technique, the presence of contaminations and the polymerization shrinkage stresses of the adhesive and resin composite. Moreover, the bonding conditions or surface conditioning are interrelated with the bonding substrate and the application method of the composite. The bonding conditions, surface conditioning or the adhesive interface can be evaluated by different methods such as subjecting the samples to bond strength tests, margin analysis and/or the evaluation of shrinkage stresses of composites (Armstrong et al. 2010; Braga et al. 2005; Braga et al. 2010; Roulet et al. 1989). The following research articles deal with individual aspects and diverse investigation methods associated with the bonding conditions of composite restorations.

2.1.1 Bond strength of adhesives upon astringent contamination

Caries removal in close proximity to the gingiva might lead to its injury and subsequent bleeding. The adhesive bonding of a composite restoration needs a clean and dry field for proper wetting of the tooth surface and formation of a hybrid layer. Surface contaminations by saliva, blood or hemostatic agents reduce the adhesive bond integrity (Chang et al. 2010). In order to stop the gingival bleeding and to proceed with the restorative procedure astringents are commonly used. This research evaluated the in vitro shear bond strength of two types of adhesives to contaminated bovine dentin with different dental astringent agents (Xu et al. 2015).

> Xu X, Chen Q, Lederer A, Bernau C, Lai G, **Kaisarly D**, Dent DM, Kunzelmann KH. 2015. Shear bond strength of two adhesives to bovine dentin contaminated with various astringents. Am J Dent. 28(4):229-234.

The universal adhesive Scotchbond Universal Adhesive (3M ESPE) used in self-etch mode and the etch-and-rinse adhesive OptiBond FL (Kerr) were used with each adhesive belonging to a different bonding technique. The first group was the non-contamination group and five dental astringents were applied in the contamination groups 25% $Al_2(SO_4)_3$ (Orbat sensitive), 25% $AlCl_3$ (Racestyptine), 10% $AlCl_3$ (Roeko Gingiva Liquid), 15.5% $Fe_2(SO_4)_3$ (Astringedent) and $AlCl_3$ Paste (Astringent Retraction Paste). The choice of these astringents was based on differences in composition, concentration and consistency (liquid or paste). The astringents were applied (1 min) to the dentin surface, rinsed with water spray (20 s), followed by application of the respective adhesive and building of composite cylinders that were subjected to shear force (Micro Shear Tester) after 1 day and 1 week storage in wet environment at 37°C. The shear bond strength values (MPa) were recorded and statistically analyzed (three-way ANOVA; etchant, contaminant, storage time). In the self-etching adhesive groups, all astringents negatively affected the bond strength values but in the etch-and-rinse adhesive groups the astringent contamination did not affect the dentin bonding.

The universal adhesive Scotchbond Universal Adhesive contains 10-methacryloyloxydecyl dihydrogen phosphate (MDP) monomers that form an ionic bond between the calcium on dentin and the phosphate groups on MDP polymers (Yoshida et al. 2012). The contamination with an aluminum containing astringent leads to substitution of calcium ions with aluminum ions that cannot be rinsed with water because they are bonded ionically to dentin. Thus, less calcium is present for bonding which explains the lower bond strength values in the self-etch groups. Aluminum ions also have a greater water affinity.

Furthermore, $AlCl_3$ or its hydrolysis can lead to the hydrolysis of the ester group in MDP which can result in bond deterioration (Teshima 2010). The aluminum ions are easily hydrolyzed and upon rinsing the astringent with water, the pH rises and the aluminum ions can form aluminum hydroxide precipitates that are assembled on the surface. However, upon etching with phosphoric acid, the pH decreases and the precipitate dissolves as aluminum ions that can be washed off. Additionally, acid etching removes the smear layer and opens the dentinal tubules facilitating the micromechanical retention and the formation of resin tags by the adhesive. These resin tags are specific to the etch-and-rinse bonding approach and the shear bond strength test is vulnerable to the presence of resin tags. This might explain the bond strength values similar to the control group.

In the clinical situation of severe bleeding when moisture can only be controlled using astringent agents the etch-and-rinse approach is recommended rather than the use of a self-etch adhesive. Prior etching with phosphoric acid can counteract contamination with hemostatic agents (e.g. $AlCl_3$).

2.1.2 Bonding conditions after self-limiting caries excavation

Conventionally, caries excavation is performed using high-speed diamond burs and low-speed carbide burs (Ricketts and Pitts 2009). Recently, polymers burs have been developed for selective removal of only demineralized dentin and for preserving sound dentin (Dammaschke et al. 2006). Because polymer burs are less hard than healthy dentin the excavation using a polymer bur is self-limiting and only the affected dentin is removed (Tsolmon 2008). Thus, polymer burs are more conservative than conventional carbide burs (Ferraz et al. 2015; Tsolmon 2008). Being minimally invasive is in agreement with recent recommendations of the International Caries Consensus Collaboration (ICCC) that proposes the selective caries removal only as required to obtain a stable restoration (Schwendicke et al. 2016). Furthermore, the arrest of carious lesions can occur upon proper sealing (Bakhshandeh et al. 2012; Maltz et al. 2012; Mertz-Fairhurst et al. 1998).

After self-limiting caries excavation with a polymer bur the tooth surface, i.e. the bonding substrate (dentin), is covered with a marked smear layer (Silva et al. 2006; Toledano et al. 2012; Tsolmon 2008). Due to its increased thickness, the smear layer might impede the diffusion of the bonding agent, thus, resulting in a deficient hybrid layer resulting in impaired bonding characteristics or unfavorable bonding conditions. Universal adhesives can be applied in the self-etch mode or in combination with previous acid etching in the etch-and-rinse mode. The acid etching is able to remove the thicker smear layer that was formed after polymer bur use (Li et al. 2011; Sherawat et al. 2014).

This research examined the adhesive bonding of a universal adhesive to residual affected dentin after using a polymer bur for the self-limiting caries excavation in human teeth compared to using a carbide bur (Wohlleb et al. 2020).

> Wohlleb T, **Kaisarly D**, Rösch P, Kunzelmann K-H. 2020. Self-limiting caries excavation with a polymer bur: Adhesive bonding to residual dentin. International Journal of Adhesion and Adhesives. 98(4):102509.

A universal adhesive (Scotchbond Universal, 3M Deutschland) was applied in either self-etch or etch-and-rinse mode and a bulk-fill composite was applied (Tetric EvoCeram Bulk Fill, Ivoclar Vivadent). Microtensile bond strength (µTBS) was tested and margin analysis was assessed before and after artificial aging. The volumetric polymerization shrinkage percentage and the shrinkage vectors were evaluated using micro-CT scans. Scanning electron microscopy (SEM) images displayed the bonded interface.

The μTBS test presented no significant difference between the tested excavation methods neither at baseline nor after fatigue simulation. When used in the self-etch mode, the universal adhesive was compromised by the smear layer's quality. All groups had > 99% perfect margins in dentin and enamel, thus, the excavation methods had no influence on the marginal integrity. These results were predictable because the area that was excavated by the polymer bur or carbide bur only formed part of the bonded area that was otherwise surrounded by sound tissue. This is the explanation for the finding that the excavation method did not influence the marginal adaptation of the composite restoration in these in vitro procedures.

Micro-CT examination revealed no significant difference between both groups regarding the volumetric shrinkage (1.9 - 2.5%) and the shrinkage vectors were directed towards the bonded area. The volumetric shrinkage percentage and the observed areas of volumetric shrinkage were in concordance with earlier investigations of volumetric shrinkage in class-II cavities (Al Sunbul et al. 2016; Algamaiah et al. 2017; Hirata et al. 2015b). The caries excavation with the polymer bur resulted in a more irregular dentin surface and a thicker smear layer than that obtained with the carbide bur. Nevertheless, the bond strength values, the marginal adaptation of the restorative material to the tooth structure, and the volumetric polymerization shrinkage percentage were similar.

The caries excavation by different bur types creates topographic changes in the dental substrate (dentin surface) that might affect the adhesive bond quality. Caries excavation with a polymer bur did not negatively influence the bonding accomplishment to residual affected dentin. Additional etching according to the etch-and-rinse concept and placing cavity margins in sound dentin can further strengthen the interfacial adaptation leading to further reliability.

2.2 Research related to the application method

The succeeding research was dealing with the influence of different application methods of bulk-fill composites on their polymerization shrinkage. The previously addressed factors were related to the cavity characteristics and the bonding substrates which are dictated by the tooth and the carious lesion. However, the choice of the bonding conditions or surface conditioning and the application technique are subject to the dentist's decision making (Kaisarly 2021).

2.2.1 Shrinkage stresses of composites

Bulk-fill composites have been invented in order to reduce application times because they can be applied and cured in thicker increments (≥ 4 mm). The materials have optimizations in their photoinitiator systems that allow for greater depth of cure than conventional composites. Furthermore, matrix and filler modifications (more translucency and less fillers) in addition to the incorporation of stress relaxators lead to controlling the shrinkage stresses. Smart dentin replacement (SDR, Dentsply) was the first clinically well-accepted bulk-fill composite, it has a lower volumetric polymerization shrinkage than hybrid composites and lower shrinkage stresses than those in other bulk-fill composites (Ilie and Hickel 2011; Rizzante et al. 2019; Zorzin et al. 2015).

In the pregel phase the composite is able to compensate for the polymerization shrinkage by its flow, but in the postgel phase the composite becomes rigid and shrinkage stresses build up because the composite is adhesively bonded to the cavity walls. Thus, strain can occur within the composite and/or debonding from cavity walls due to stress release (Ferracane 2005). The time to gelation usually occurs within the first seconds after light-curing and its duration depends on each material. The longer the time to gelation, the more time the composite has to flow without stresses (Braga et al. 2005; Hellwig et al. 2018; Keßler et al. 2019). Other factors that influence the shrinkage stresses are the C-factor, the composite volume, the composition of the composite and the degree of cure (Braga et al. 2006; Keßler et al. 2019).

Recently, a bulk-fill composite with glass fibers (up to 1 mm long), EverX Posterior (EverX), has been introduced. The manufacturer claims that the randomly oriented fibers are being reoriented horizontally upon the tamping pressure during composite application into the cavity. In consequence, anisotropy is expected to be transmitted through the fiber orientation (horizontal) and the shrinkage stress is anticipated to be reduced in accordance with the fiber direction. This research investigated the effect of fiber incorporation on the polymerization shrinkage stresses (contraction stresses) of bulk-fill and fiber reinforced composites (Keßler et al. 2019).

> Keßler A, **Kaisarly D**, Hickel R, Kunzelmann KH. 2019. Effect of fiber incorporation on the contraction stress of composite materials. Clin Oral Investig. 23(3):1461-1471.

It was hypothesized that EverX has the same amount of volumetric shrinkage, time to gelation and temperature rise as the other bulk-fill composites and that the shrinkage stress of the fiber-containing composite should differ from that of the other composites due to the anisotropic shrinkage stress distribution. For this purpose, the shrinkage stresses, the time to gelation and the increase in temperature of two experimental resin-based composites were evaluated and compared to those of bulk-fill and conventional composites in two clinically relevant cavity configurations. The two cavity configurations ($2 \times 4 \times 4$ mm^3 and $4 \times 4 \times 4$ mm^3, respective configuration value ½ and ⅓) were corresponding to a cavity depth for the incremental (2 mm) and the bulk (4 mm) application.

The shrinkage stresses were measured by a stress-strain analyzer (SSA T80) (Chen et al. 2001) for two experimental composites, eight bulk-fill composites (EverX Posterior, Filtek Bulk Fill, SDR, SonicFill, Tetric EvoCeram Bulk Fill, Venus Bulk Fill, X-tra base, and X-tra Fill) and one conventional composite (Filtek Supreme XTE). The experimental materials were based on the composite EverX Posterior and modifications were made to the fiber and filler content.

The values of the shrinkage stresses ranged from 1.00 MPa in SDR to 4.07 MPa in Filtek Supreme XTE (2-mm cavities) and from 0.97 MPa in SDR to 2.49 MPa in the experimental composite with fibres (4-mm cavities). Lowest shrinkage stress values were obtained in SDR, but significantly higher values were measured in the experimental composite with fibers than in the experimental composite without fibers but with fillers in both cavity configurations. The values of the time to gelation ranged from 1.31 s in Filtek Supreme XTE to 4.05 s in SDR (2-mm cavities) and from 1.39 s in X-tra Fill to 3.84 s in X-tra base (4-mm cavities).

The lower shrinkage stress in the larger configuration can be explained by the different degree of cure, which was lower in all the 4-mm cavities than in the 2-mm cavities. Only SDR and Venus Bulk Fill showed no significant differences in the shrinkage stress values.

It should be noted that these two bulk-fill composites had the least filler content by weight (68 wt% and 65 wt% respectively) of the investigated composites.

The time to gelation is influenced by the incorporated fillers, the reactive matrix, or structures promoting rapid network formation such as bulky monomers and fillers which behave as “solid crosslinkers” helping rapid gelation (Takahashi et al. 2011). Examples of solid crosslinkers involve the silanized glass fibres in EverX Posterior and the prepolymerized fillers in Tetric EvoCeram Bulk Fill. Prepolymerized fillers have a relatively low modulus of elasticity and lead to low stress values (Takahashi et al. 2011).

The fiber-containing bulk-fill material EverX Posterior had greater shrinkage stresses and a shorter time to gelation than investigated non-fiber-containing bulk-fill composites. The orientation of the shrinkage stress of EverX Posterior did not differ from the non-fiber-containing bulk-fill composites. Taking into account the high shrinkage stresses it could be shown that the fibres were not horizontally aligned throughout the tested composite. Another explanation would be the presence of a too small amount of fibers in the material to demonstrate an effect. In general, bulk-fill composites showed lower shrinkage stress levels than the conventional composite.

2.2.2 Bulk versus incremental application of flowable composites

The polymerization shrinkage and shrinkage stresses can be assessed by investigating a material sample (de Melo Monteiro et al. 2011; Watts and Marouf 2000; Watts et al. 2003). Shrinkage can be considered with technical methods only on geometrically standardized specimens. These geometric shapes do not take into account complex cavity geometry such as mod-cavities or the influence of differences in adhesion to enamel and dentin, which can also be examined on teeth. The actual polymerization shrinkage of a composite restoration can only be determined when the composite is applied inside the prepared cavity in the tooth. For each cavity, the specific boundary conditions of the respective situation apply (Kaisarly 2021; Kaisarly et al. 2018a; Kaisarly et al. 2019; Kaisarly et al. 2018b; Van Ende et al. 2013; Van Meerbeek et al. 2003).

The polymerization reaction of composites goes hand in hand with the polymerization shrinkage and results in shrinkage stresses in the material and at the cavity boundaries (de Gee et al. 1981; Sakaguchi and Powers 2012). The incremental application of composites is performed to reduce the adverse consequences of polymerization shrinkage. The incremental application of composites compensates in parts for the polymerization shrinkage by the subsequent increment and improves the degree of conversion (Braga et al. 2005; Davidson and Feilzer 1997; Ferracane 2005; 2008; Porte et al. 1984). A maximum of a 2-mm-thick increment is crucial for conventional composites to obtain an adequate degree of polymerization (Kaisarly and Gezawi 2016; Rueggeberg et al. 2017).

Bulk-fill composites can be placed with a 4 mm thickness due to their sufficient depth of cure. This research investigated the concept of bulk versus incremental application of flowable bulk-fill and conventional composites (Kaisarly et al. 2021a). In the following studies, the concept of stress relief due to modulus of elasticity (low versus high) was investigated.

> **Kaisarly D**, El Gezawi M, Keßler A, Rösch P, Kunzelmann K. 2021. Shrinkage vectors in flowable bulk-fill and conventional composites: Bulk versus incremental application. Clin Oral Investig. 25(3):1127-1139.

In this study, cylindrical cavities were prepared in extracted human third molars and bonded with an etch-and-rinse adhesive OptiBond FL (Kerr). The composites were mixed with 2 wt% silanized radiolucent glass beads that appeared as spheres and served as markers. The shrinkage vectors were evaluated as described earlier (Chiang et al. 2010; Kaisarly et al. 2018b).

In one group, SDR (Dentsply) was applied in bulk "SDR-bulk", in two more groups, the flowable composites SDR and Tetric EvoFlow (Ivoclar Vivadent) were applied in two 2-mm-thick increments. The greatest shrinkage vectors were found in the bulk application of SDR and the smallest were found in both groups of the incremental application with significant differences among the groups. Greatest linear polymerization shrinkage and shrinkage stress were observed in Tetric EvoFlow, but the time to gelation was greatest in the bulk application of SDR.

The filler volume and the modulus of elasticity influence the composite's elastic deformation (Stansbury 2012). SDR has a relatively low filler content (68 wt%) compared with other bulk-fill materials (74 – 86%) (Keßler et al. 2019). SDR's greater flexibility can be attributed to the modified urethane dimethacrylate matrix and a polymerization modulator. The urethane dimethacrylate matrix leads to a slow polymerization rate producing less polymerization shrinkage stresses than those of conventional flowable composites (Cramer et al. 2011; Moorthy et al. 2012).

Despite the shrinkage stress reduction in SDR, the greater shrinkage vectors in the bulk application compared to the incremental applications could be related to the greater volume of the restorative material (Van Ende et al. 2015). Other researchers also observed better internal adaptation when bulk-fill composites were applied in increments compared with bulk application (Alqudaihi et al. 2019). Debonding might occur when shrinkage stresses exceed the interfacial bonds and facilitate the shrinkage movement (Kaisarly et al. 2018a; Kaisarly et al. 2018b). The unlike shrinkage behavior of the two increments could be related to the different bonding substrates available (Kaisarly et al. 2019). The first composite increment was adhesively bonded to dentin at the cavity floor and walls, whereas the second composite increment was bonded to composite at its lower side and to enamel margins and dentin cavity walls. Bonding to enamel might restrict the composite movement and allow for more movement or debonding at the dentin wall and/or floor (Chiang et al. 2010).

The combination of several investigation methods displayed a broader image of the interaction of factors in bonded composite restorations. The lower shrinkage stress and the delayed gelation time of SDR caused material flow. The shorter time to gelation of Tetric EvoFlow induced greater shrinkage stresses and shorter shrinkage vectors despite the greater linear shrinkage. Thus, the measurement of polymerization shrinkage of a composite sample does not necessarily reflect the actual shrinkage behavior of composite that is adhesively bonded to the cavity boundaries.

It can be concluded that the application method influences the polymerization shrinkage behavior of composites. The bulk application of composite had greater values of shrinkage vector magnitude and a greater tendency for debonding at the cavity floor. In the incremental application, debonding of composites is less likely to happen than with the bulk application as seen in SEM images. Therefore, the incremental application should remain the gold standard of composite insertion even with bulk-fill composites in class-I cavities.

2.2.3 Bulk versus incremental application of hybrid composites

This research was the continuation of the aforementioned study and investigated the bulk versus incremental application of hybrid composites that have a higher modulus of elasticity than flowable composites. The bulk application of a composite increases the C-factor which can lead to debonding from the cavity boundaries. Clinical success of a restoration depends on a firm bond to the tooth structure. The shrinkage stress relievers are incorporated in bulk-fill composites to absorb shrinkage stress and could contribute to a good marginal quality (Roggendorf et al. 2011; Todd and Wanner 2014). The shrinkage vectors and the volumetric polymerization shrinkage percentage of a hybrid composite and a hybrid bulk-fill composite were evaluated in different application methods (Kaisarly et al. 2021b).

Kaisarly D, El Gezawi M, Rösch P and Kunzelmann K-H. 2021. Shrinkage vectors and volumetric shrinkage percentage of differently applied composites. International Journal of Adhesion and Adhesives. 105(3):102793.

As previously described, cylindrical cavities were prepared in third molars and bonded with an etch-and-rinse adhesive OptiBond FL (Kerr). Cavities were restored with a 4-mm bulk-fill composite of Tetric EvoCeram Bulk Fill (Ivoclar Vivadent), with two 2-mm increments of the same bulk-fill composite and with two 2-mm increments of a hybrid composite Tetric EvoCeram (Ivoclar Vivadent). The shrinkage vectors and the volumetric shrinkage were evaluated from the same micro-CT scans. The bulk application resulted in greater shrinkage vectors than in the incremental application but the volumetric polymerization shrinkage was indifferent among the groups. Less debonding from the cavity floor and/or walls was observed among the incrementally applied groups.

Bulk-fill composites have similar polymerization shrinkage values to conventional composites applied incrementally, the incremental application yields higher bond strength values and minimal gap formation (Alqudaihi et al. 2019; Bakhsh et al. 2013; Junior et al. 2018; Miguez et al. 2004; Van Ende et al. 2016). The volumetric shrinkage percentage of Tetric EvoCeram Bulk Fill is comparable to that measured by others in bonded restorations who have calculated similar values (Hirata et al. 2015b; Sampaio et al. 2019).

The shrinkage vector evaluation displayed significant difference between the groups but the volumetric shrinkage evaluation displayed no significant difference concerning the application method. The percentage of the volumetric polymerization shrinkage as a sole measure is not indicative of the region where the material has shrunk. There is a discrepancy between the evaluation methods that can be related to the anisotropic shrinkage that is visualized via the shrinkage vectors but cannot be quantified by the volumetric evaluation. The volumetric polymerization shrinkage percentage cannot locate the area of shrinkage.

The different results suggest that the shrinkage vector evaluation is more sensitive than the volumetric evaluation. Furthermore, the shrinkage vector evaluation is able of displaying internal movements within different areas of the restoration. These areas can be put in relation to the boundary conditions of the respective restoration, such as the substrate to which the restoration was bonded to (enamel or dentin), the bonding conditions (adhesive) or the cavity configuration. It can be visualized whether the shrinkage was related to the restoration's free surface that has less restriction in movement than bonded restoration's surfaces (Cho et al. 2011; Kaisarly et al. 2018a; Kaisarly et al. 2019; Kaisarly et al. 2018b).

Debonding as a consequence of stress relaxation can lead to gap formation that can result in an anisotropic shrinkage pattern (Van Ende et al. 2015).

Tetric EvoCeram Bulk Fill was compared to other bulk-fill composites of variable viscosities in occlusal cavities and had the smallest percentage of volumetric shrinkage and least gap formation at the cavity floor (Sampaio et al. 2019). On applying larger increments shrinkage stresses were lower in bulk-fill composites (Rizzante et al. 2019), which is in agreement with a previous investigation (Keßler et al. 2019).

In deep cavities, cavities with an irregular floor, endodontic access cavities or deeply situated cavity margins of class-II cavities, the bulk-fill composites are definitely beneficial because of their improved depth of cure. Nevertheless, the incremental application of bulk-fill composites is advised to minimize the polymerization shrinkage and preserving the tooth-restoration bond integrity. The incremental application remains the gold standard of hybrid resin composites in class-I cavities.

2.2.4 Application of flowable liners in class-I restorations

The application of a flowable composite liner beneath a composite restoration was performed when dental adhesives were unfilled and their application resulted in a very thin layer (Choi et al. 2000; Montes et al. 2001). The flowable composite liners are hereafter referred to as "flowable liners". The application of a layer of a low viscosity composite as a flowable liner beneath a composite restoration was advocated to reduce the polymerization shrinkage stresses at the bonded interface (Braga and Ferracane 2004; Leevailoj et al. 2001). In vitro, the flowable liner resulted in a stress-absorbing layer and the stress-relieving effect may be due to the elastic flowable composite layer or its better initial adaptation and/or bonding to cavity boundaries (Labella et al. 1999; Montes et al. 2001). On the other hand, in vivo, no improvement was detected upon applying the flowable liner (Lindberg et al. 2005; Perdigao et al. 2004; Stefanski and van Dijken 2012; van Dijken and Pallesen 2011). It should be noted that current dental adhesives contain fillers and subsequently have a greater film thickness than early unfilled adhesives.

This study investigated the influence of using flowable composite liners on the shrinkage vectors and the adaptation of bulk-fill composites in class-I restorations. Variation in thickness of the flowable liner and subsequent bulk-fill composite was evaluated (Kaisarly et al. 2021c).

Kaisarly D, Meierhofer D, El Gezawi M, Rösch P, Kunzelmann KH. 2021. Effects of flowable liners on the shrinkage vectors of bulk-fill composites. Clin Oral Investig. 25(8):4927-4940.

In this study human third molars were divided into five groups, cylindrical cavities were prepared as described before and bonded with a universal adhesive (Adhese Universal, Ivoclar Vivadent) in self-etch mode. The flowable liners, or bulk-fill composites of low modulus of elasticity, Tetric EvoFlow Bulk Fill and SDR were used to line the cavity floor. Tetric EvoCeram Bulk Fill was used as the filling material of high modulus of elasticity in all cavities. The applications included bulk application (group 1), a thin flowable liner (0.5 mm) Tetric EvoFlow Bulk Fill in group 2, and a thin flowable liner Tetric EvoFlow Bulk Fill with two increments of hybrid bulk-fill composite in group 3. In the last two groups the flowable liner was 2 mm thick; in group 4 the flowable liner was Tetric EvoFlow Bulk Fill and in group 5 it was SDR because SDR is a widely used restorative material. Tetric EvoCeram Bulk Fill is also a popular bulk-fill composite and Tetric EvoFlow Bulk Fill is the bulk-fill version of Tetric EvoFlow which has been used in the earlier shrinkage vector evaluation studies and is widely used in the clinical practice (Chiang et al. 2010; Kaisarly et al. 2018a; Kaisarly et al. 2019; Kaisarly et al. 2018b). The shrinkage vectors were evaluated as described earlier (Chiang et al. 2010; Kaisarly et al. 2018b).

The bulk application resulted in greatest shrinkage vectors. A thin flowable liner (group 2) resulted in larger overall shrinkage vectors for the whole restoration than a thick flowable liner (group 4). A thin flowable liner and the incremental application of TBF (group 3) yielded the smallest shrinkage vectors. SDR (group 5) yielded slightly smaller shrinkage vectors for the whole restoration than those observed in group 4. The largest interfacial gap was observed in the bulk application (group 1) which can be related to the largest shrinkage vectors. The groups with a flowable liner were not free of debonding, but to a much lesser extent. The smallest area of debonding from the cavity floor was seen in group 3 in which the thin flowable liner was covered with two further increments of the hybrid bulk-fill composite.

Based on our findings, the application of a flowable liner resulted in smaller shrinkage vectors in the flowable liner and the following increment(s). This phenomenon could be explained by the relative elasticity of the flowable liner that would allow flexibility of the material or better adhesion. The bulk application resulted in larger shrinkage vectors than the groups with a flowable liner. Smaller shrinkage vectors were seen in the thin flowable liner, while larger shrinkage vectors were associated with the thicker layer of flowable liner. This observation might be related to the composite volume and the intermediate zone of a flowable composite of greater elasticity.

The application of the flowable liner resulted in an increment of varying thickness; larger volumes were present in the cavity corners or line angles yielding concave surface that was closely adapted to the cavity walls and floor as was observed earlier (Kaisarly et al. 2021a). A resembling appearance was reported in thick adhesive layers (Sumitani et al. 2018). It was assumed that the decreased viscosity facilitated the close adaptation of flowable composites (Labella et al. 1999; Montes et al. 2001).

The application of a flowable liner and the thickness variation of the flowable liner and/or composite influenced the polymerization shrinkage. The thinner the flowable liner or composite increment, the smaller the shrinkage vectors. The better performance or the smaller shrinkage vectors of the thin layer of flowable liner could be attributed to low shrinkage, which results in little stress and little prior damage to the adhesive interface. At the same time, good adaptation or adhesion to dental substrates results in better adaptation of the entire restoration. Flowable liner in thin (0.5 mm) or thick layer (2 mm) resulted in favorable shrinkage patterns and good adaptation to the cavity boundaries. Therefore, the application of a flowable liner beneath bulk-fill composites is advisable.

2.2.5 Different applications of bulk-fill composites in class-II restorations

The former investigations dealt with different application methods of flowable and hybrid bulk-fill composites in cylindrical class-I cavities in teeth (Kaisarly et al. 2021a; Kaisarly et al. 2021b; Kaisarly et al. 2021c). In class-II cavities, it is very important to build the anatomical contour of the tooth and to restore a tight proximal contact with the neighboring tooth (Loomans et al. 2006). Until today, there is not one ideal insertion technique but rather variable methods of composite application are recommended such as the incremental composite application beginning from the deepest part of the proximal box or by building a proximal wall first by centripetal build-up (Bichacho 1994; Ritter et al. 2019b). This study investigated different common application methods of bulk-fill composites in class-II cavities and their effects on the polymerization shrinkage. Upon building the proximal wall, the favorable C-factor of class-II cavities may become unfavorable (Kaisarly et al. 2022).

Kaisarly D, Langenegger R, Litzenburger F, Heck K, El Gezawi M, Rösch P, Kunzelmann KH. 2022. Effects of the application method on the shrinkage vectors and volumetric shrinkage of bulk-fill composites in class-II restorations. Dent Mater. 38(1):79-93.

Occluso-proximal class-II cavities were prepared in human third molars and bonded with a universal adhesive (Adhese Universal, Ivoclar Vivadent) in self-etch mode. The composite application methods are described as follows: in group 1: bulk application of the hybrid bulk-fill composite Tetric EvoCeram Bulk Fill (TBF, Ivoclar Vivadent). Group 2: first building the proximal wall (TBF), then filling the occlusal cavity (TBF). Group 3: applying a thin layer of flowable liner of the flowable bulk-fill composite Tetric EvoFlow Bulk Fill (TEF, Ivoclar Vivadent) followed by bulk filling with TBF. Group 4: application of the flowable liner (TEF), proximal wall (TBF) and the occlusal cavity (TBF). Group 5: bulk application of the commonly used flowable bulk-fill composite SDR (3 mm, Dentsply) and adding a capping layer (TBF, 1 mm). Shrinkage vectors and volumetric polymerization shrinkage were evaluated as described earlier (Chiang et al. 2010; Kaisarly et al. 2021b; Kaisarly et al. 2018b).

Greatest shrinkage vectors were identified in SDR in group 5, followed by the bulk application of TBF in group 1. Changing the boundaries of a class-II cavity by first building the proximal wall (group 2) yielded smaller shrinkage vectors than in the bulk application (group 1). Building the proximal wall has changed the boundary conditions, here the cavity boundaries and bonded surfaces, and resulted in less free surfaces. Debonding at the tooth-restoration interface (group 2) could be explained by the presence of more bonded surfaces with possible higher shrinkage stresses despite the same C-factor.

The groups with successive composite applications (groups 2 - 4) had smaller shrinkage vectors. Applying a thin layer of flowable liner below the hybrid bulk-fill composite resulted in small shrinkage vectors (group 3) that were comparable to group 2 and improved adaptation of the flowable liner to the cavity boundaries. Preceding the proximal wall buildup by a thin layer of flowable liner (group 4) caused even smaller shrinkage vectors and resulted in a perfectly bonded tooth-restoration interface. an improved adaptation to the cavity boundaries. Smallest shrinkage vectors were calculated in the covering layer TBF of group 5.

The incremental composite application decreased the mean values of shrinkage vectors, which is in agreement with previous studies (Kaisarly et al. 2021a; Kaisarly et al. 2021b; Kaisarly et al. 2021c). Shrinkage vectors and the volumetric shrinkage percentage differed significantly among the groups. Volumetric shrinkage was greatest in SDR followed by the flowable liner TEF of group 4 and group 3 and smallest in the incremental application of TBF in group 4. A greater number of increments corresponds to a smaller respective volume of each and smaller shrinkage vectors (Kaisarly et al. 2021c).

The volumetric polymerization shrinkage measured in the current study is in agreement with measured values in class-II restorations in earlier studies (Algamaiah et al. 2017; Hirata et al. 2015a; Wohlleb et al. 2020). Unlike the precursor study, significant differences were obtained in both evaluation methods which can be attributed to variations in volume and shape of the respective increments in addition to variable elastic moduli of the flowable and hybrid bulk-fill composites (Kaisarly et al. 2021b). In summary, more factors were mixed that could contribute to observing the significant differences.

According to the theory of the C-factor, the proximal wall should have resulted in more shrinkage of the occlusal increment but the results of the current study indicated otherwise. Building a proximal resin composite wall yielded smaller shrinkage vectors than the bulk application. Applying a thin flowable liner decreased the shrinkage vectors, even more when building a proximal wall. A thin flowable liner is recommended when building a proximal resin composite wall. This raises the question about the validity of the concept of the C-factor, or whether other factors are more important such as achieving good wetting of the adhesive, the composite composition or the layering of composite increments.

3 Summary and outlook

The polymerization shrinkage of composite restorations is influenced by several factors that can be represented by boundary conditions of composite restorations. These boundary conditions can be divided into factors related to the cavity geometry, the bonding substrates, the bonding conditions or surface conditioning and the application and curing methods. The focus of previous research was mainly related to the cavity configuration, the bonding substrate and the bonding conditions.

The aim of this research was to investigate the polymerization shrinkage of dental composite restorations, with the focus on bulk-fill composites, and its clinical consequences or implications. In the first part, the research was mainly related to the bonding conditions or surface conditioning, while in the second part, the focus was on the application techniques.

In the first part, the influence of several astringents on the shear bond strength of adhesives to bovine dentin was studied. The contamination by the astringents showed a detrimental effect on the bond strength when applied in the self-etch approach, but using an etch-and-rinse approach yielded good bond strength values. Thus, acid etching removed astringent remnants that interfered with the adhesion to dentin. The choice of adhesive should depend on the situation.

The method of caries excavation affects the bonding substrate and consequently the bonding conditions. Caries excavation was performed with a polymer bur or with a carbide bur. The adhesive bonding of a universal adhesive (in self-etch and etch-and-rinse modes) to residual affected dentin was evaluated. All applied tests, μ-TBS, marginal integrity and micro-CT evaluation, presented no significant difference between the excavation methods.

The second part focused on the effect of different application methods on the polymerization shrinkage of bulk-fill composites in class-I and class-II cavities. The polymerization reaction of composites goes hand in hand with the polymerization shrinkage and results in shrinkage stresses at the cavity boundaries. The incremental application of composites reduces the C-factor, compensates in part for the polymerization shrinkage by the later increment and improves the degree of conversion.

Bulk-fill composites can reduce application times because they can be applied and cured in thicker increments (≥ 4 mm). These materials have optimizations in their photoinitiator systems, matrix and filler modifications in addition to the incorporation of stress relaxators that lead to controlling the shrinkage stresses. Experimental composites incorporating glass fibres were compared to other composites. Bulk-fill composites showed lower shrinkage stress levels than conventional composites. However, the incorporation of fibers had no positive impact on the shrinkage stresses, i.e. stress reduction and the time to gelation.

The bulk versus incremental application of a flowable bulk-fill (SDR) and a conventional composite in a cylindrical class-I cavity as a worst-case scenario were evaluated by the shrinkage vectors. The shrinkage vectors were significantly greater in the bulk application and smaller in both composites when applied in increments. Despite the shrinkage stress reduction in SDR, the greater shrinkage vectors in the bulk application compared to the incremental applications, could be related to the greater volume and C-factor of the restorative material. Debonding might occur when shrinkage stresses exceed the interfacial bonds and facilitate the shrinkage movement. The lower shrinkage stress and the delayed gelation time of SDR permitted material flow, but the shorter time to gelation of Tetric EvoFlow induced greater shrinkage stresses and shorter shrinkage vectors despite the greater linear shrinkage. The measurement of the volumetric polymerization shrinkage of a composite sample does not necessarily reflect the actual shrinkage behavior of composite that is adhesively bonded to the cavity boundaries.

Furthermore, the continuation of the previously described study investigated the shrinkage vectors and the volumetric polymerization shrinkage percentage of hybrid composites and hybrid bulk-fill composites when applied in increments versus in bulk. Significantly greater shrinkage vectors were observed in the bulk application, whereas no significant differences were seen in the percentage of the volumetric polymerization shrinkage concerning the application method. The inconsistency between the evaluation methods can be attributed to the anisotropic shrinkage, which is visualized via the shrinkage vectors but cannot be quantified by the volumetric evaluation. The percentage of the volumetric polymerization shrinkage as a sole measure is not indicative of the region where the material has shrunk. The incremental application of resin composites remains the gold standard in class-I cavities. In cavities with an irregular cavity floor, in endodontic access cavities, in deep proximal boxes and wherever there is a great distance between the light guide and the composite, the use of bulk-fill composites is useful.

The application of a layer of a low viscosity composite as a flowable composite liner beneath a composite restoration was advocated to reduce the polymerization shrinkage stresses at the bonded interface. The flowable composite liners are referred to as “flowable liners”. The effects of flowable composites in thin and thick increments below bulk-fill composites were evaluated. The application of a flowable liner resulted in smaller shrinkage vectors in both the flowable liner and the following increment(s). This phenomenon could be explained by the relative elasticity of the flowable liner. The greatest discrepancy between values of shrinkage vectors were seen between the application in bulk without any flowable liner and the groups with a flowable liner. The thinner the flowable liner or composite increment, the smaller the shrinkage vectors. The smaller shrinkage vectors of the thin layer of flowable liner could be attributed to low shrinkage, which results in little stress and little prior damage to the adhesive interface. At the same time, good adhesion results in better adaptation of the entire restoration. This observation might be related to the composite volume and the intermediate zone of a flowable composite of greater elasticity. Thus, flowable liners act as a stress reliever, while thick layers of flowable liner had a more pronounced stress-relieving effect. From this aspect, it is recommended to apply a flowable composite liner (thin or thick) beneath bulk-fill composites, preferably incrementally with separate light curing of each increment.

A further study investigated different common application methods of bulk-fill composites in class-II cavities and their effects on the polymerization shrinkage. Upon building the proximal wall, the favorable C-factor of class-II cavities may become more unfavorable. In the current study the bulk application resulted in greatest shrinkage vectors. According to the theory of the C-factor, the proximal wall should have resulted in more shrinkage of the occlusal increment but the results of the current study indicated otherwise. Building a proximal resin composite wall yielded smaller shrinkage vectors than the bulk application. Applying a thin flowable liner decreased the shrinkage vectors, even more when building a proximal wall. A thin flowable liner is recommended when building a proximal resin composite wall. This raises the question about the validity of the concept of the C-factor, or whether other factors are more important such as achieving good wetting of the adhesive, the composite composition or the layering of composite.

4 Zusammenfassung und Ausblick

Die Polymerisationsschrumpfung von Kompositfüllungen wird von mehreren Faktoren beeinflusst, welche durch die Rahmenbedingungen von Kompositfüllungen dargestellt werden können. Diese Rahmenbedingungen können in Faktoren unterteilt werden, die sich auf die Kavitätengeometrie, das Substrat, die Haftbedingungen, bzw. die Konditionierung der Haftflächen und die Applikations- und Aushärtungsmethode beziehen. Der Fokus der bisherigen Forschung lag hauptsächlich auf der Kavitätenkonfiguration, dem Substrat und der Haftbedingung.

Ziel dieser Forschungsarbeit war es, die Polymerisationsschrumpfung von Kompositfüllungen, mit dem Schwerpunkt auf Bulk-Fill-Kompositen, und deren klinische Folgen bzw. Implikationen zu untersuchen. Im ersten Teil bezog sich die Forschung hauptsächlich auf die Haftbedingungen, bzw. die Konditionierung der Haftflächen, während im zweiten Teil der Schwerpunkt auf den Applikationstechniken lag.

Im ersten Teil wurde der Einfluss verschiedener blutstillender Mittel auf die Scherhaftung von Adhäsiven an Rinderdentin untersucht. Die Kontamination durch die Adstringentien wirkte sich nachteilig auf die Haftfestigkeit aus, wenn die Adhäsive im Selbstätzverfahren appliziert wurden, während das Etch-and-Rinse Verfahren gute Haftfestigkeitswerte lieferte, da die Säureätzung Adstringensreste entfernte, die die Haftung zum Dentin beeinträchtigten. Dementsprechend sollte die Wahl des Adhäsivs von der jeweiligen Situation abhängen.

Die Methode der Kariesexkavation beeinflusst das Haftsubstrat und folglich die Haftbedingung. Die Kariesexkavation in einer Kavität wurde mit einem Polymerbohrer (Polybur) oder mit einem Rosenbohrer durchgeführt, anschließend wurde der adhäsive Verbund eines Universaladhäsivs zum restlichen betroffenen Dentin bewertet. Alle angewandten Tests, Mikrozugtest (μTBS), Randspaltanalyse und Mikro-CT-Auswertung, zeigten keinen signifikanten Unterschied zwischen beiden Exkavationsmethoden.

Der zweite Teil befasste sich mit der Auswirkung verschiedener Applikationsmethoden auf die Polymerisationsschrumpfung von Bulk-Fill-Kompositen in Klasse-I- und Klasse-II-Kavitäten. Die Polymerisationsreaktion von Kompositen geht mit der Polymerisationsschrumpfung einher und führt zu Schrumpfspannungen an den Kavitätenrändern. Der inkrementelle Einsatz von Kompositen reduziert den C-Faktor, kompensiert teilweise die Polymerisationsschrumpfung durch das spätere Inkrement und verbessert den Konversionsgrad.

Bulk-Fill-Komposite können die Applikationszeiten reduzieren, da sie in größeren Schichtstärken (≥ 4 mm) appliziert und ausgehärtet werden können. Diese Materialien weisen Optimierungen in ihren Photoinitiatorsystemen, Matrix- und Füllstoffmodifikationen sowie die Einarbeitung von Stressrelaxatoren auf, die zur Kontrolle der Schrumpfungsspannungen führen. Experimentelle Komposite, die Glasfasern enthalten, wurden mit anderen Kompositen verglichen. Bulk-Fill-Komposite zeigten geringere Schrumpfungsspannungen als konventionelle Komposite. Allerdings hatte die Einarbeitung von Fasern keinen positiven Einfluss auf die Schrumpfungsspannungen und die Zeit bis zum Erreichen des Gelpunkts.

Die Bulk- versus inkrementelle Applikation eines fließfähigen Bulk-Fill-Materials (SDR) und eines konventionellen Komposits in einer zylindrischen Klasse-I-Kavität (worst-case scenario) wurden anhand der Schrumpfungsvektoren bewertet. Die Schrumpfungsvektoren waren bei der Bulk-Applikation signifikant größer, bei der inkrementellen Applikation bei beiden Kompositen kleiner. Trotz der Reduktion der Schrumpfungsspannung bei SDR könnten die größeren Schrumpfungsvektoren bei der Bulk-Applikation, im Vergleich zu den inkrementellen Applikationen, mit dem größeren Volumen des Füllungsmaterials zusammenhängen. Ablösungen könnten auftreten, wenn die Schrumpfungsspannungen die Grenzflächenhaftkräfte übersteigen. Die geringere Schrumpfungsspannung und die verzögerte Gelation von SDR ermöglichten den Materialfluss, die kürzere Zeit bis zur Gelation von Tetric EvoFlow induzierte größere Schrumpfungsspannungen und kürzere Schrumpfungsvektoren trotz der größeren linearen Schrumpfung. Die Messung der Polymerisationsschrumpfung einer Kompositprobe spiegelt nicht das tatsächliche Schrumpfungsverhalten von Komposit wider, wenn es an den Kavitätengrenzen verklebt ist.

Des Weiteren wurden in der Fortsetzung der zuvor beschriebenen Studie die Schrumpfungsvektoren und der prozentuale Anteil der volumetrischen Polymerisationsschrumpfung von hybriden Kompositen und hybriden Bulk-Fill-Kompositen bei der Applikation in Inkrementen gegenüber der Applikation im Bulk untersucht. Signifikant größere Schrumpfungsvektoren wurden bei der Bulk-Applikation beobachtet, während für die Messung der volumetrischen Polymerisationsschrumpfung keine signifikanten Unterschiede in Bezug auf die Applikationsmethode festgestellt wurden.

Die Inkonsistenz zwischen den Auswertemethoden ist jedoch auf die anisotrope Schrumpfung zurückzuführen, die über die Schrumpfungsvektoren visualisiert wird, aber durch die volumetrische Auswertung nicht lokalisiert quantifiziert werden kann. Der summarische prozentuale Anteil der volumetrischen Polymerisationsschrumpfung als alleiniges Maß ist nicht aussagekräftig für den Bereich, in dem das Material stärker geschrumpft ist. Daher bleibt die inkrementelle Anwendung von Kunststoffkompositen der Goldstandard bei Klasse-I-Kavitäten. In Kavitäten mit unregelmäßigem Kavitätenboden, in endodontischen Zugangskavitäten, in tiefen approximalen Kästen und überall dort, wo ein großer Abstand zwischen Lichtleiter und Komposit besteht, ist die Verwendung von Bulk-Fill-Kompositen sinnvoll.

Die Anwendung einer Schicht eines niedrigviskösen Komposits als „fließfähiger Liner" unter einer Kompositfüllung kann befürwortet werden, um die Schrumpfungsspannungen am Adhäsivverbund zu reduzieren. Die Auswirkungen von fließfähigen Kompositen in dünnen und dicken Schichten unter Bulk-Fill-Kompositen wurden untersucht. Die Anwendung eines fließfähigen Komposits führte zu kleineren Schrumpfungsvektoren sowohl im fließfähigen Komposit als auch in dem/den folgenden Inkrement(en). Dieses Phänomen konnte durch die relative Elastizität des fließfähigen Komposits erklärt werden. Die größte Diskrepanz zwischen den Werten der Schrumpfungsvektoren wurde zwischen der Anwendung in Bulk ohne fließfähigen Komposit und den Gruppen mit einem fließfähigen Komposit festgestellt. Je dünner das fließfähige Komposit oder das Inkrement des hybriden Komposits, desto kleiner die Schrumpfungsvektoren. Die kleineren Schrumpfungsvektoren der dünnen Schicht fließfähigen Komposits können auf die geringe Schrumpfung zurückgeführt werden, die zu geringen Spannungen und Vorschädigungen am Adhäsiv Verbund führt. Gleichzeitig führt eine gute Benetzung am Zahn zu einer besseren Anpassung der gesamten Restauration. Diese Beobachtung könnte mit dem Volumen des Komposits und der elastischeren Zwischenschicht eines fließfähigen Komposits zusammenhängen. Somit wirken fließfähige Komposite spannungsabbauend, wobei dicke Schichten fließfähiger Komposite eine ausgeprägter spannungsabbauende Wirkung hatten. Daher ist es empfehlenswert, ein fließfähiges Komposit (dünn oder dick) unter Bulk-Fill-Komposite anzuwenden, vorzugsweise inkrementell separat ausgehärtet.

In einer weiteren Studie wurden verschiedene übliche Anwendungsmethoden von Bulk-Fill Kompositen in Klasse-II Kavitäten und deren Auswirkungen auf die Polymerisationsschrumpfung untersucht. Beim Aufbau der proximalen Wand kann der günstige C-Faktor von Klasse-II-Kavitäten ungünstiger werden. In der aktuellen Studie führte die Bulk-Applikation zu den größten Schrumpfungsvektoren. Nach der Theorie des C-Faktors hätte die proximale Wand zu einer stärkeren Schrumpfung des okklusalen

Inkrements führen müssen, aber die Ergebnisse dieser Studie deuten auf das Gegenteil hin. Der Aufbau einer proximalen Kompositwand führte zu kleineren Schrumpfungsvektoren als die Bulk-Applikation. Das Auftragen eines dünnen, fließfähigen Komposits verringerte die Schrumpfungsvektoren, noch kleinere Schrumpfungsvektoren wurden erreicht, wenn eine dünne Schicht fließfähigen Komposits vor dem Aufbau einer proximalen Wand aufgetragen wurde. Eine dünne Schicht fließfähigen Komposits wird für den Aufbau einer proximalen Kompositwand empfohlen. Dies wirft die Frage auf, ob das Konzept des C-Faktors möglicherweise nicht gültig ist oder ob andere Faktoren wichtiger sind, wie beispielsweise das Erreichen einer guten Benetzung des Adhäsivs oder die Zusammensetzung des Komposits selbst oder die Schichtung des Komposits.

5 List of abbreviations

C-factor	Configuration factor
FDI	Fédération dentaire internationale: World Dental Federation
FEA	Finite element analysis
Flowable liner	Flowable composite liner
ICCC	International Caries Consensus Collaboration
LVDT	linear variable differential transformer
MDP	10-methacryloyloxydecyl dihydrogen phosphate
micro-CT	Microcomputed tomography
min	Minute
mm	Millimeter
Mod-cavity	Mesio-occluso-distal cavity
MPa	Mega Pascal
s	Second
SDR	Smart dentin replacement
SEM	Scanning electron microscopy
TBF	Tetric EvoCeram Bulk Fill
TEF	Tetric EvoFlow Bulk Fill
wt	weight
µm	Micrometer
µTBS	Microtensile bond strength
%	Percent

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Xu X, Chen Q, Lederer A, Bernau C, Lai G, Kaisarly D, Dent DM, Kunzelmann KH. 2015. Shear bond strength of two adhesives to bovine dentin contaminated with various astringents. Am J Dent. 28(4):229-234

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7 Original research of the cumulative habilitation thesis

7.1 Shear bond strength of two adhesives to bovine dentin contaminated with various astringents

Xu X, Chen Q, Lederer A, Bernau C, Lai G, **Kaisarly D**, Dent DM, Kunzelmann KH. 2015. Am J Dent. 28(4):229-234, IF 1.194

Source: https://pubmed.ncbi.nlm.nih.gov/26437505/

Abstract

Purpose: To investigate the in vitro shear bond strength of two adhesives to bovine dentin contaminated with various astringents.

Methods: 120 adult bovine incisors were collected and cut to obtain 240 specimens. The specimens were randomly divided into a self-etch adhesive group (N=120) and a total-etch adhesive group (N=120). Both of the groups were divided into the following six subgroups: the non-contamination group and the contamination groups 25% $Al_2(SO_4)_3$ (Orbat sensitive), 25% $AlCl_3$ (Racestyptine), 10% $AlCl_3$ (Roeko Gingiva Liquid), 15.5% $Fe_2(SO_4)_3$ (Astringedent) and $AlCl_3$ Paste (Astringent Retraction Paste, N=20 in each subgroup). Each astringent was applied for 1 minute to the dentin surface before rinsing with water spray for 20 seconds. The respective adhesive was then applied according to the manufacturer's instructions. Two composite cylinders were shaped with a mold, cured on the dentin surface of each specimen and sheared off after 1 day and 1 week storage. The shear bond strengths (MPa) were recorded and analyzed with ANOVA.

Results: In the self-etching adhesive group, all astringents showed negative effects on dentin bonding ($p < 0.05$). Astringent contamination did not have a negative effect on dentin bonding in the total-etch adhesive group ($p > 0.05$).

Clinical significance: In the case of severe bleeding, when moisture control is only possible with astringent agents, a total-etch adhesive is preferred over the self-etch adhesive.

7.2 Self-limiting caries excavation with a polymer bur: Adhesive bonding to residual dentin

Wohlleb T, **Kaisarly D**, Rösch P, Kunzelmann K-H. 2020. International Journal of Adhesion and Adhesives. 98(4):102509.https://doi.org/10.1016/j.ijadhadh.2019.102509, IF 3.189

Source: https://www.sciencedirect.com/science/article/abs/pii/S0143749619302593

Abstract

Objectives: The aim of this study was to evaluate the bonding of an universal adhesive to residual affected dentin after polymer bur excavation of natural caries lesions in human teeth.

Materials and methods: Caries excavation with a polymer bur and with a carbide bur were compared. A microtensile bond strength (μ-TBS) test was performed in a split-tooth design (n = 20/group). A universal adhesive (Scotchbond Universal, 3M-Deutschland, Neuss/Germany) was applied in either self-etch (SE) or total-etch (TE) mode. Qualitative and quantitative margin analysis was assessed before/after fatigue simulation (n = 8/group). Micro-CT examination was performed before/after polymerization of class-II restorations (Tetric EvoCeram BulkFill, Ivoclar-Vivadent, Schaan/Liechtenstein) (n = 6/group). Volumetric shrinkage and shrinkage vectors were calculated. The internal interface was analyzed under scanning electron microscopy after cutting the teeth.

Results: The μ-TBS test revealed no significant difference between excavation methods. Mean tensile strengths (MPa) were: polymer-bur/SE = 16.0, polymer-bur/TE = 16.7, carbide-bur/SE = 15.5, carbide-bur/TE = 20.3, dentin/SE = 13.9, dentin/TE = 24.1. Margin analysis rated all groups >99% of perfect margin in dentin and enamel, no influence of excavation methods was found. Micro-CT examination revealed no difference between groups concerning volumetric shrinkage (1.9–2.5%). The shrinkage direction was towards the bonded area. Polymer bur excavation resulted in an irregular surface and thicker smear layer than with carbide bur.

Conclusion: Caries excavation with a polymer bur does not negatively affect bonding performance to residual affected dentin. Etching with phosphoric acid can further strengthen the interface.

7.3 Effect of fiber incorporation on the contraction stress of composite materials

Keßler A, **Kaisarly D**, Hickel R, Kunzelmann KH. 2019. Clin Oral Investig. 23(3):1461-1471.10.1007/s00784-018-2572-1, IF 2.812

Source: https://pubmed.ncbi.nlm.nih.gov/30120604/

Abstract

Objectives: This study aimed to assess the effects of fiber incorporation on the contraction stress (CS), time to gelation (TG), and temperature rise (TR) features of two experimental resin-based composites (RBCs) in comparison to those of bulk-fill RBCs and conventional RBCs in simulated, clinically relevant cavities.

Materials and methods: CS over 300 s, TG and TR were assessed by a stress-strain analyzer (SSA T80) in two cavity configurations (2 × 4 × 4 mm3/4 × 4 × 4 mm3/configuration value 1_2 and 1_3) for two experimental RBCs, eight bulkfill RBCs (EverX Posterior, Filtek Bulk Fill, SDR, SonicFill, Tetric EvoCeram Bulk Fill, Venus Bulk Fill, X-tra base, and X-tra Fill) and one RBC (Filtek Supreme XTE) by light curing (1200 mW/cm2) (n = 10). The experimental materials used were based on EverX Posterior with modifications made to the fiber and filler content. Statistical analyses were performed via ANOVA; multiple pair-wise comparisons were performed via Tukey's test, and homogeneous subsets were identified ("multcomp" package, R).

Results: CS values ranged from 1.00 to 4.07 MPa (2 × 4 × 4 mm^3) and from 0.97 to 2.49 MPa (4 × 4 × 4 mm^3); TG values ranged from 1.31 to 4.05 s (2 × 4 × 4 mm^3) and from 1.39 to 3.84 s (4 × 4 × 4 mm^3). SDR values showed lowest stress values in both cavity configurations. The experimental composite with fibers presented significantly higher stress values than did the experimental composite without fibers.

Conclusion: Bulk-fill RBCs showed lower levels of stress than did conventional RBCs. The incorporation of fibers had no positive impact on the CS and TG.

Clinical relevance: Appropriate material selection may be essential to clinical success because certain RBCs exhibit higher CS, TG, and TR values.

7.4 Shrinkage vectors in flowable bulk-fill and conventional composites: Bulk versus incremental application

Kaisarly D, El Gezawi M, Keßler A, Rösch P, Kunzelmann K. 2021. Clin Oral Investig. 25(3):1127-1139.https://doi.org/10.1007/s00784-020-03412-3, IF 3.573 - 2020

Source: https://pubmed.ncbi.nlm.nih.gov/32653992/

Abstract

Objectives: Sufficient depth of cure allows bulk-fill composites to be placed with a 4-mm thickness. This study investigated bulk versus incremental application methods by visualizing shrinkage vectors in flowable bulk-fill and conventional composites.

Materials and methods: Cylindrical cavities (diameter = 6 mm, depth = 4 mm) were prepared in 24 teeth and then etched and bonded with OptiBond FL (Kerr, Italy). The composites were mixed with 2 wt% radiolucent glass beads. In one group, smart dentin replacement (SDR, Dentsply) was applied in bulk "SDR-bulk" (n = 8). In two groups, SDR and Tetric EvoFlow (Ivoclar Vivadent) were applied in two 2-mm-thick increments: "SDR-incremental" and "EvoFlow-incremental." Each material application was scanned with a micro-CT before and after light-curing (40 s, 1100 mW/cm^2), and the shrinkage vectors were computed via image segmentation. Thereafter, linear polymerization shrinkage, shrinkage stress and gelation time were measured (n = 10).

Results: The greatest shrinkage vectors were found in "SDR-bulk" and "SDR-increment2," and the smallest were found in "SDR-increment1-covered" and "EvoFlow-increment1-covered." Shrinkage away from and toward the cavity floor was greatest in "SDR-bulk" and "EvoFlow-increment2," respectively. The mean values of the shrinkage vectors were significantly different between groups (one-way ANOVA, Tamhane's T2 test, $p < 0.05$). The linear polymerization shrinkage and shrinkage stress were greatest in Tetric EvoFlow, and the gelation time was greatest in "SDR-bulk."

Conclusions: The bulk application method had greater values of shrinkage vectors and a higher debonding tendency at the cavity floor.

Clinical relevance: Incremental application remains the gold standard of composite insertion.

7.5 Shrinkage vectors and volumetric shrinkage percentage of differently applied composites

Kaisarly D, El Gezawi M, Rösch P and Kunzelmann K-H. 2021. International Journal of Adhesion and Adhesives. 105(3):102793.https://doi.org/10.1016/j.ijadhadh.2020.102793, IF 3.189 - 2020

Source: https://doi.org/10.1016/j.ijadhadh.2020.102793

Abstract

Bulk-fill composites can be placed at a thickness of 4 mm due to their sufficient depth of cure. The aim of this study was to investigate the effects of bulk versus incremental application methods on the shrinkage vectors and the percentage of volumetric polymerization shrinkage of the composites. Twelve molars were divided into three groups (n = 4), and cylindrical cavities (diameter = 6 mm, depth = 4 mm) were prepared, etched and bonded with OptiBond FL (Kerr). Cavities were restored with a 4-mm bulk-fill composite of Tetric EvoCeram Bulk Fill (TBF, Ivoclar Vivadent) designated as “TBF-bulk”, with two 2-mm increments of a bulk-fill composite designated as “TBF-incremental”, and with two 2-mm increments of a hybrid composite Tetric EvoCeram (TEC, Ivoclar Vivadent) designated as “TEC-incremental”. Each material application was scanned twice in a micro-CT (uncured and cured states), and inherent air bubbles served as markers. Scans were subjected to image segmentation to calculate the shrinkage vectors and the percentage of volumetric polymerization shrinkage. Significantly greater mean values of the shrinkage vectors were observed in “TBF-bulk”, followed by “TBF-increment1”, with no difference between the remaining increments of the groups (ANOVA, Tamhane's T2, $p < 0.001$); the percentage of volumetric polymerization shrinkage did not differ among the groups (ANOVA, Tamhane's T2, $p = 0.759$). Bulk application resulted in greater shrinkage vectors than in the incremental applications, despite the volumetric evaluation displaying no difference regarding the application methods. The discrepancy between the evaluation methods can be explained by anisotropic shrinkage, which is displayed through the shrinkage vectors but cannot be quantified by the volumetric evaluation. Incremental application of resin composites remains the gold standard in class-I cavities.

7.6 Effects of flowable liners on the shrinkage vectors of bulk-fill composites

Kaisarly D, Meierhofer D, El Gezawi M, Rösch P, Kunzelmann KH. 2021. Clin Oral Investig. 25(8):4927-4940.10.1007/s00784-021-03801-2, IF 3.573 - 2020

Source: https://pubmed.ncbi.nlm.nih.gov/33506426/

Abstract

Objectives: This investigation evaluated the effect of flowable liners beneath a composite restoration applied via different methods on the pattern of shrinkage vectors.

Methods: Forty molars were divided into five groups (n = 8), and cylindrical cavities were prepared and bonded with a self-etch adhesive (AdheSe). Tetric EvoCeram Bulk Fill (TBF) was used as the filling material in all cavities. The flowable liners Tetric EvoFlow Bulk Fill (TEF) and SDR were used to line the cavity floor. In gp1-TBF, the flowable composite was not used. TEF was applied in a thin layer in gp2-fl/TEF + TBF and gp3-fl/TEF + TBFincremental. Two flowable composites with a layer thickness of 2 mm were compared in gp4-fl/TEF + TBF and gp5-fl/SDR + TBF. TEF and SDR were mixed with radiolucent glass beads, while air bubbles inherently present in TBF served as markers. Each material application was scanned twice by micro-computed tomography before and after light curing. Scans were subjected to image segmentation for calculation of the shrinkage vectors.

Results: The absence of a flowable liner resulted in the greatest shrinkage vectors. A thin flowable liner (gp2-fl/TEF + TBFbulk) resulted in larger overall shrinkage vectors for the whole restoration than a thick flowable liner (gp4-fl/TEF + TBF). A thin flowable liner and incremental application (gp3-fl/TEF + TBFincremental) yielded the smallest shrinkage vectors. SDR yielded slightly smaller shrinkage vectors for the whole restoration than that observed in gp4-fl/TEF + TBF.

Conclusions: Thick flowable liner layers had a more pronounced stress-relieving effect than thin layers regardless of the flowable liner type.

Clinical relevance: It is recommended to apply a flowable liner (thin or thick) beneath bulk-fill composites, preferably incrementally.

7.7 Effects of application method on shrinkage vectors and volumetric shrinkage of bulk-fill composites in class-II restorations

Kaisarly D, Langenegger R, Litzenburger F, Heck K, El Gezawi M, Rösch P, Kunzelmann KH. Dent Mater. 38(1):79-93.https://doi.org/10.1016/j.dental.2021.10.013, IF 5.304 – 2020

Source: https://pubmed.ncbi.nlm.nih.gov/34836696/

Abstract

Objectives: Upon initial proximal wall construction, the favorable C-factor of class-II cavities may become unfavorable. This study investigated the application method on bulk-fill resin composite polymerization shrinkage.

Methods: Occluso-proximal class-II cavities were prepared in 40 molars and bonded with a self-etch adhesive (Adhese Universal). The study groups varied according to the resin composite application: group-1: bulk application, Tetric EvoCeram Bulk Fill (TBF); group-2: proximal wall construction (TBF) and occlusal cavity filling (TBF); group-3: thin flowable liner layer, Tetric EvoFlow Bulk Fill (TEF) and bulk filling (TBF); group-4: flowable liner (TEF), proximal wall (TBF), occlusal cavity (TBF); and group-5: bulk application, SDR (3 mm) and capping layer (TBF, 1 mm). Each resin composite increment was scanned twice using micro-CT (uncured, cured 40 s) at a resolution of 16 µm. Shrinkage vectors and volumetric polymerization shrinkage were evaluated and statistically analyzed (one-way ANOVA). SEM images were used to investigate the tooth-restoration interface.

Results: Shrinkage vectors differed significantly among the groups and were greatest in gp5-fl/SDR (47.6 µm), followed by gp1-TBF (23.8 µm) and least in gp5-fl/SDR+TBF (11.1 µm). Volumetric shrinkage varied significantly with the use of SDR (gp5-fl/SDR: 2.6%) and TEF (gp4-fl/TEF: 2.5%) to TBF (gp4-fl/TEF+wl/TBF: 0.6%) in the incremental application.

Significance: Building a proximal resin composite wall yielded smaller shrinkage vectors than the bulk application. Applying a thin flowable liner decreased the shrinkage vectors, even more when building a proximal wall. A thin flowable liner is recommended when building a proximal resin composite wall.

8 Complete list of publications

8.1 Original research as first or last author (9)

1. **Kaisarly D**, Langenegger R, Litzenburger F, Heck K El Gezawi M, Rösch P, Kunzelmann KH. 2022. Effects of application method on shrinkage vectors and volumetric shrinkage of bulk-fill composites in class-II restorations, Dent Mater. 38(1):79-93. (IF 5.304 - 2020)
2. **Kaisarly D**, Meierhofer D, El Gezawi M, Rösch P, Kunzelmann KH. 2021. Effects of flowable liners on the shrinkage vectors of bulk-fill composites. Clin Oral Investig. 25(8):4927-4940. (IF 3.573 - 2020)
3. **Kaisarly D**, El Gezawi M, Rösch P and Kunzelmann K-H. 2021. Shrinkage vectors and volumetric shrinkage percentage of differently applied composites. International Journal of Adhesion and Adhesives. 105(3):102793. (IF 3.189 - 2020)
4. **Kaisarly D**, Elgezawi M, Haridy R, Elembaby A, Aldegheishem A, Alsheikh R, Al-mulhim K,. 2021. Reliability of Class-II Bulk-fill Composite Restorations with and without Veneering: A Two-Year Randomized Clinical Control Study, Oper Dent. 46(5):491-504. (IF 2.213 - 2020)
5. **Kaisarly D**, El Gezawi M, Keßler A, Rösch P, Kunzelmann K. 2021. Shrinkage vectors in flowable bulk-fill and conventional composites: Bulk versus incremental application. Clin Oral Investig. 25(3):1127-1139. (IF 3.573 - 2020)
6. **Kaisarly D**, El Gezawi M, Nyamaa I, Rosch P, Kunzelmann KH. 2019. Effects of boundary condition on shrinkage vectors of a flowable composite in experimental cavity models made of dental substrates. Clin Oral Investig. 23(5):2403-2411. (IF 2.812)
7. **Kaisarly D**, El Gezawi M, Xu X, Rösch P, Kunzelmann K-H. 2018. Shrinkage vectors of a flowable composite in artificial cavity models with different boundary conditions: Ceramic and teflon. Journal of the Mechanical Behavior of Biomedical Materials. 77(1):414-421. (IF 3.485)
8. **Kaisarly D**, El Gezawi M, Lai G, Jin J, Rösch P, Kunzelmann KH. 2018. Effects of occlusal cavity configuration on 3D shrinkage vectors in a flowable composite. Clin Oral Investig. 22(5):2047-2056. (IF 2.453)
9. El Gezawi M, Haridy R, Abo Elazm E, Al-Harbi F, Zouch M, **Kaisarly D**. 2018. Microtensile bond strength, 4-point bending and nanoleakage of resin-dentin

interfaces: Effects of two matrix metalloproteinase inhibitors. Journal of the Mechanical Behavior of Biomedical Materials. 78(2):206-213. (IF 3.485)

8.2 Original research as co-author (10)

1. Litzenburger F, Heck K, **Kaisarly D**, Kunzelmann KH. 2022. Diagnostic validity of early proximal caries detection using near-infrared imaging technology on 3d range data of posterior teeth. Clin Oral Investig. 26(1):543-553. (IF 3.573 - 2020)
2. Haridy R, Abdalla MA, **Kaisarly D,** Gezawi ME. 2021. A cross-sectional multicenter survey on the future of dental education in the era of COVID-19: Alternatives and implications. J Dent Educ. 85(4):483-493.10.1002/jdd.12498. (IF 2.264 - 2020)
3. Hojabri N, **Kaisarly D**, Kunzelmann K-H. 2021. Adhesion and whitening effects of P11-4 self-assembling peptide and HAP suspension on bovine enamel. Clin Oral Investig. 25(5):3237-3247. (IF 3.573 - 2020)
4. Wohlleb T, **Kaisarly D**, Rösch P, Kunzelmann K-H. 2020. Self-limiting caries excavation with a polymer bur: Adhesive bonding to residual dentin. International Journal of Adhesion and Adhesives. 98(4):102509. (IF 3.189)
5. Keßler A, **Kaisarly D**, Hickel R, Kunzelmann KH. 2019. Effect of fiber incorporation on the contraction stress of composite materials. Clin Oral Investig. 23(3):1461-1471. (IF 2.812)
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7. Al-Harbi F, **Kaisarly D**, Bader D, El Gezawi M. 2016. Marginal integrity of bulk versus incremental fill class II composite restorations. Oper Dent. 41(2):146-156. (IF 2.893)
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10. Lai G, **Kaisarly D**, Xu X, Kunzelmann KH. 2014. Microct-based comparison between fluorescence-aided caries excavation and conventional excavation. Am J Dent. 27(1):12-16. (IF 0.85)

8.3 Review of literature (3)

1. **Kaisarly D**, Gezawi ME. 2016. Polymerization shrinkage assessment of dental resin composites: A literature review. Odontology. 104(3):257-270. (IF 1.602)
2. El Gezawi M, Wölfle UC, Haridy R, Fliefel R, **Kaisarly D**. 2019. Remineralization, regeneration, and repair of natural tooth structure: Influences on the future of restorative dentistry practice. ACS Biomaterials Science & Engineering. 5(10):4899-4919. (IF 4.152)
3. **Kaisarly D**. 2021. Polymerisationsschrumpfung – Aktueller Stand und klinische Konsequenzen. Quintessenz Zahnmedizin. (06):638-648.

8.4 Case report (1)

1. Auerbacher M, Kakoschke TK, Hickel R, **Kaisarly D**. 2022. Treatment Plan and Challenges in Full-Mouth Rehabilitation of a Quadriplegic Patient: A Clinical Report. J Prosthodont. 31(3):183-189. (IF 2.752 - 2020)

8.5 Conference presentations (18)

1. 87th General Session & Exhibition of the IADR, Miami, USA, April 2009, oral presentation: Finite Element Analysis and Mechanical Assessment of Restored Compromised Enamel, **Kaisarly D**, Moussa T, Hashem A, Elragi A
2. IADR 91st General Session, Seattle, Washington, USA, March 2013, oral presentation: Shrinkage Vectors in Different Cavity Configurations, **Kaisarly D**, Rösch P, Hickel R, Kunzelmann KH
3. IADR 91st General Session, Seattle, Washington, USA, March 2013, poster: Composite Shrinkage Vector Patterns in Cavities With Optimal Adhesion, **Kaisarly D**, El Gezawi M, Rösch P, Hickel R, Kunzelmann KH
4. Conseuro Paris 2013, May 2013, poster: Composite Shrinkage Vector Patterns in Non-Adhesive Teflon Cavities, **Kaisarly D**, Rösch P, Hickel R, Kunzelmann KH

5. CED-IADR 46th Meeting of CED, Florence, Italy, Sept 2013, oral presentation: Composite Shrinkage Vectors in Silanized Ceramic Cavities with Layer of Bonding Agent, **Kaisarly D**, El Gezawi M, Rösch P, Hickel R, Kunzelmann KH
6. CED-IADR 46th Meeting of CED, Florence, Italy, Sept 2013, oral presentation: MTBS-Analysis of Class-II Bulk Versus Incremental Fill Resin Composite Restorations, El Gezawi M, **Kaisarly D**, Al-Harbi F, Bader D
7. CED-IADR 46th Meeting of CED, Florence, Italy, Sept 2013, oral presentation: Cervical Marginal-Integrity of Bulk Versus Incremental Fill Class-II Resin-Composite Restorations, El Gezawi M, **Kaisarly D**, Al-Harbi F, Bader D
8. SCANCO World-Wide User Meeting, Appenzell, Switzerland, Oct 2013, oral presentation: Shrinkage Vectors In An Improvised Cavity With Enamel Floor, **Kaisarly D**, El Gezawi M, Rösch P, Hickel R, Kunzelmann KH
9. IADR 92nd General Session, Cape Town, South Africa, June 2014, poster: Color Stability and Surface Integrity of Bulk Versus Incremental-fill resin-Composites; Al-Saleh H, **Kaisarly D**, Bader D, Arrajie A, El Gezawi M
10. IADR 92nd General Session, Cape Town, South Africa, June 2014, poster: Effect of Home Bleaching on Color and Surface Integrity of Bulkfill Composites; Al-Saleh H, **Kaisarly D**, El Gezawi M
11. IADR 93rd General Session, Boston, MA, USA, March 2015, oral presentation: Shrinkage Vectors in Bulk versus Incrementally Applied SDR Bulkfill Composite, **Kaisarly D**, El Gezawi M, Rösch P, Hickel R, Kunzelmann KH
12. IADR 93rd General Session, Boston, MA, USA, March 2015, oral presentation: Shrinkage Vectors in Cavities with Different Bonding Substrates; **Kaisarly D**, El Gezawi M, Rösch P, Hickel R, Kunzelmann KH
13. CED-IADR/NOF Oral Health Research Congress Vienna, Austria, Sept 2017, oral presentation: Reliability of two anti-MMP Dentin Treatments: 4-point bending, microtensile bond strength and nanoleakage; El Gezawi M, Haridy R, Abo Elazm E, Al-Harbi F, Zouch M, **Kaisarly D**
14. IADH2018 Dubai, UAE, Aug 2018, poster: The oral rehabilitation of a 46 years old quadriplegic patient with implant supported dentures, Auerbacher M, Hickel R, **Kaisarly D**, #146
15. IADR 97th General Session, Vancouver, BC, Kanada, June 2019, oral presentation: Effects of flowable liner on shrinkage vectors of bulkfill composites, **Kaisarly D**, Meierhofer D, El Gezawi M, Rösch P, Kunzelmann KH

16. CED-IADR/NOF Oral Health Research Congress in Madrid, Spain, Sept 2019, oral presentation: Shrinkage vectors and volumetric shrinkage percentage of differently applied composites, **Kaisarly D**, El Gezawi M, Rösch P, Kunzelmann KH
17. Digital 10th Conseuro 2021, Antalya, Turkey, April 2021, poster: Shrinkage vectors in bulk-fill composites restoring endodontic access cavities. **Kaisarly D**, Kanamori Y, Meierhofer D, Langenegger R, El Gezawi M, Rösch P, Kunzelmann KH. EP-071
18. IADR 99th General Session, Boston, MA, USA, July 2021, poster presentation: Effects of application methods and C-factor on the shrinkage vectors of bulk-fill composites in class-II restorations. **Kaisarly D**, Langenegger R, El Gezawi M, Rösch P, Kunzelmann KH, #549

Underlined name: presenter

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