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REVIEW ARTICLE

Factors affecting polymerization of resin-based composites: A literature review

Maan M. AlShaafi *

Department of Restorative Dental Sciences, College of Dentistry, King Saud University, Riyadh, Saudi Arabia

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Abstract *Aim:* The aim of this review was to help clinicians improve their understanding of the polymerization process for resin-based composites (RBC), the effects of different factors on the process and the way in which, when controlled, the process leads to adequately cured RBC restorations.

Methods: Ten factors and their possible effects on RBC polymerization are reviewed and discussed, with some recommendations to improve that process. These factors include RBC shades, their light curing duration, increment thickness, light unit system used, cavity diameter, cavity location, light curing tip distance from the curing RBC surface, substrate through which the light is cured, filler type, and resin/oral cavity temperature.

Conclusion: The results of the review will guide clinicians toward the best means of providing their patients with successfully cured RBC restorations.

Contents

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* Address: P.O. Box 60169, Riyadh 11545, Saudi Arabia.
E-mail address: malshaafi@ksu.edu.sa.

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1. Introduction

In the history of operative dentistry, gold alloy was used as one of the first options for dental restorative material in the early fourth millennium BC (Platt, 2001). Restorative dentistry materials and treatment have developed continuously since then. In the 18th century, a product called "D'Arcets Mineral Cement" was used as a direct restorative material (Baum et al., 1995). This material was later improved, developed, and modified by Greene Vardiman Black, the so-called father of dentistry. In 1896, Black formulated the basic amalgam alloy composition, which, although it was modified after 80 years, is still the main formula for restorative material (Duke et al., 1982). Although the amalgam restorations delivered acceptable clinical performance, the search for a material that could both bond to tooth structure and match its color continued. As long ago as the early 1900s, silicate cement material was developed that partially matched the shade of the teeth and was thus found to be adequate, especially for restoring anterior teeth (Baum et al., 1995). It offered a good color match, but it tended to stain fast, was very irritant to pulp owing to its high acidity, and dissolved slowly in the oral environment.

Unfilled resin restorations came later, overcoming the disadvantages of its predecessor, having good solubility in the oral cavity and being highly polishable (so fewer stains) and repairable. However, it did have a number of drawbacks, including high polymerization shrinkage and a high wear rate (Baum et al., 1995). This material continued to be used until Dr. Rafael ("Ray") Bowen introduced resin composites in the late 1950s (Bowen, 1956). The resin matrix (Bis-GMA) was a major breakthrough, along with the bonding concept, in modern esthetic dentistry (Anusavice et al., 2013). Resin-based composite (RBC) goes from a plastic phase to a semisolid phase through a process called polymerization. The start of this process involves reactions that produce free radicals. These free radicals can be the result of energy (heat or light) or chemical activation. Producing an adequately cured/polymerized resin increment(s) is considered the main criterion for a successful RBC restoration. This is achieved mainly by having a proper degree of convergence, which is defined as the percentage of carbon–carbon double bond ($C{=}C$) that is converted to carbon–carbon single bond ($C{-}C$) (Anusavice et al., 2013). During polymerization of the RBC, most of the monomer should be converted into polymers. However, some monomers remain unreacted within the polymeric matrix. The usual degree of convergence (DC) for dimethacrylate polymers ranges between 43% and 75% (Imazato et al., 2001; Peutzfeldt et al., 2000; Ruyter and Svendsen, 1978). A high degree of monomer convergence is vital to enhance the physical and mechanical properties, color stability, and biocompatibility of the RBC material (Krifka et al., 2012; Moraes et al., 2008; Schneider et al., 2008).

Many factors affect the degree of polymerization of RBCs, including the shade, light curing duration, increment thickness, light unit system used, cavity diameter, cavity location, light curing tip distance from the curing RBC surface, substrate through which the light is cured (e.g., curing through ceramic, enamel, or dentin), filler type, and temperature (AlQahtani et al., 2013; AlQahtani et al., 2015; Chang and Kim, 2014; Reges et al., 2008; Rueggeberg et al., 1993). In this literature review, the discussion focuses on the abovementioned factors and their effect on the quality of cured RBCs.

1.1. Effect of resin shade

A major advantage of RBC restoration is its esthetic properties and tooth color matching (Johnston and Reisbick, 1997). Different shades of RBC are available with different translucencies, to provide better shade matching with surrounding tooth structures, thus enhancing the esthetic of the restoration.

For darker shades in RBCs, some manufacturers have recommended increasing the light curing time. This recommendation is evidenced and supported by several studies reporting an effect of the RBC shade on the degree of monomer convergence (Ferracane et al., 1986; Guiraldo et al., 2009; Shortall, 2005). In 2009, Guiraldo et al. conducted an *in vitro* study of the effect of different Flitek Z250 RBC shades (A1, A2, A3, A3.5 and A4 vita shade guide) on the DC. They reported that darker shades exhibited lower microhardness than light shades (Guiraldo et al., 2009).

On the other hand, Ferracane et al. (1986) evaluated the effect of four different shades of three types of RBC (Macrofill (Prisma-fil), Microfill (Prisma-fine), and conventionally filled (Aurafill)) on their monomer DC. The translucency of each shade was measured with a spectrophotometer. It was concluded that the DC depended significantly on the light penetration capacity through RBC material, which is determined by its translucency and the filler-resin system (Ferracane et al., 1986). In agreement, Jeong et al. evaluated the effect of four different shades of two RBCs (Z250 and Solitaire 2), and tested shades A3, A3.5, B3, and C3 of Z250, and shades A3, A3.5, B3, and B4 of Solitaire 2. A Vickers hardness test was carried out to evaluate the DC of the RBCs indirectly. In addition, light reflection and absorbance through the materials were measured using a spectrophotometer. They found the lowest DC values with A3.5 shade of Z250 RBC, which exhibited the highest light distribution that could be related to the resin-filler system of the material (Jeong et al., 2009).

Also, Shortall studied the effect of different Filtek Z250 RBC shades on the depth of cure. Translucent RBCs showed higher microhardness values. More translucent RBCs allow more light transmission through the layers. This results in higher DC and consequently a higher microhardness value (Shortall, 2005). Moreover, Araujo Fde et al. (2006) evaluated the effect of RBC shades and location at the gingival margins (enamel or dentin) on the microleakage of Class II restorations. Sixty extracted third molars were used to prepare mesial and distal Class II cavities with an axial depth of 2 mm and one third of the buccolingual width. Gingival margins of the mesial boxes were located on the dentin (1 mm beyond the cementoenamel junction [CEJ]). However, the gingival margins of the distal boxes were located on the enamel (1 mm above the CEJ). Filtek Z250 (microhybrid composite) with different six shades (i.e., incisal, A1, A2, A3, A3.5, and A4) was used to restore the cavities. No significant differences were reported on the DC and microleakage of different Z250 shades. This indicated sufficient light transmission of the deepest layer, allowing adequate DC of the RBC. Additionally, in 2005, Aguiar et al. assessed the effect of the curing tip distance and RBC shade on the microhardness of hybrid composite (Z250) (Aguiar et al., 2005). They concluded that A1 shade showed higher microhardness values than C2 shade. This could be a result of less light penetration through the opaquer shade RBC.

In 1995, Shortall et al. evaluated the effect of different RBC shades and opacities on the DC (Shortall et al., 1995). They tested five hybrid composite RBCs and one mono-model RBC (Prisma AP.H, Brilliant, Charisma, Herculite, Pertac-Hybrid, and Z 100) of three shades (Vita A2, A3.5, and C2) and two opacities (enamel and dentin "when available"). They reported significant differences between the various RBC materials with the same shade. This could be due to different filler compositions, size, and loading (Atmadja and Bryant, 1990; Barron et al., 1992; Ruyter and Oysaed, 1982). In addition, it has been reported that the same Vita shade of different RBC products showed different color values and color differences. This could be the reason for different DC values in different RBCs with the same Vita shade (Swift et al., 1994). Shortall et al. also reported a higher DC of the enamel opacity of RBCs than that of dentin opacity with the same shade ($p < 0.05$), possibly as a consequence of different translucencies between enamel and dentin shades that could affect the light penetration through the RBC layers (Shortall et al., 1995).

From the abovementioned studies, it appears that RBC translucency and not the shade has a significant effect on light transmission through the RBCs' thickness.

1.2. Effect of light curing duration

Many *in vitro* studies have been done to determine the effect of light curing duration on RBCs' mechanical properties (Ceballos et al., 2009; Obici et al., 2004; Rasetto et al., 2001). In order for a 2 mm increment in the thickness of the RBC to have adequate polymerization, it should receive a radiant exposure within the 16–24 J/cm^2 range (Anusavice et al.; Rueggeberg et al., 1994a; Sobrinho et al., 2000). This energy (E) is calculated by multiplying the irradiance level (I) coming from the light control unit (LCU) (mW/cm^2) by its duration (T). Curing time is set depending on the irradiance level. The higher the irradiance level, the shorter the curing time needed. One of the first studies to evaluate and propose efficient irradiance levels and time exposures was conducted by Rueggeberg et al. They concluded that for a 2 mm RBC increment, 60 s of curing time was needed. This makes sense, since they used the old generation of quartz tungsten halogen (QTH) light curing units (which were the most commonly used type of curing lights until 2001), and the average of the unit's irradiance level in their experiment was 400 mW/cm^2, leading to a radiant exposure of an average of 24 J/cm^2 (Rueggeberg et al., 1994a).

In the years since then, dental light curing manufacturers have developed different light systems. Currently, light-emitting diode (LED) units are the predominant type of curing unit used by dentists worldwide. In 2004, Wiggins et al. assessed the effect of different curing methods on RBCs' DC (Wiggins et al., 2004). They compared the effect of different LCUs: high power (HP) LED, first-generation LED, conventional QTH, and HP QTH. Using HP LEDs and HP QTH LCUs, light curing of RBCs was done for 10 s. On the other hand, first-generation LEDs and conventional halogen LCUs were used to polymerize RBC samples for 20 s. Depth of cure (DOC) was assessed using a scraping test following the ISO 4049 method. They found no significant differences in the DC of RBCs that were light polymerized with different LCUs for different times. They concluded that HP LED and HP QTH LCUs could be used for half the curing time of other tested LCUs and still provide adequate DC. While Wiggins et al. used the ISO 4049 technique to test their DOC, another study by Felix et al. obtained the same results by recording the Knoop microhardness (Felix et al., 2006). They evaluated the impact of different exposure times on the microhardness of RBCs. Ten RBC Class I restorations were prepared in human extracted molars. After light polymerization, the hardness of the RBCs was evaluated using Knoop microhardness 3.5 mm from the surface. Light curing using QTH on a high power setting for half of the recommended time resulted in microhardness values of the RBC similar to the QTH on a medium power setting for the full recommended exposure time. Therefore, the authors concluded that using high power LEDs or QTH LCUs allowed sufficient curing with lower exposure times.

Ceballos et al. studied the effect of different light curing methods on the DC of microhybrid RBC (Filtek Z250) and sub-micron hybrid (Spectrum TPH) RBC materials. Samples were cured either with QTH or with LED LCUs for 20 or 40 s, and were tested using a scraping technique (according to ISO 4049) and the Vickers microhardness test at different depths. A significant effect was found of the LCU and time exposure of the curing light interaction on both RBC depth of cure and microhardness. Curing light exposure for a longer time (40 s vs. 20 s) resulted in higher microhardness values (Ceballos et al., 2009). Additionally, Zorzin et al., when testing bulk-fill RBCs, conventional condensable RBC, and a flowable RBC, concluded that increasing the curing time beyond the manufacturer's recommendations (+10–20 s) had positive effects on the DC and the microhardness of the RBCs (Zorzin et al., 2015).

With the new generation of LED units, the irradiance levels have increased, such that LED units are now capable of delivering more than 5000 mW/cm^2. Some manufacturers claim that, thanks to these high-power LEDs, curing can be done in a minimum of 1–3 s (Ilie and Stark, 2014). This claim could derive from the "exposure reciprocity law," which proposes reciprocity between irradiance levels and exposure time to achieve equivalent polymerization of RBCs. The law assumes that, provided the same radiant exposure is delivered, the DC will be the same, no matter what the time or irradiance level. This may mean less duration in light curing, resulting in higher clinical productivity. However, the question is is a minimum light curing time necessary to achieve an adequately cured restoration? The law has been evaluated extensively in the literature (Emami and Soderholm, 2003; Hadis et al., 2011; Halvorson et al., 2002; Leprince et al., 2011; Price et al., 2004; Wydra et al., 2014) and found not to apply, as it is photoinitiator-, viscosity-, and even time-dependent (D'Alpino et al., 2007; Hadis et al., 2011; Leprince et al., 2011; Wydra et al., 2014). A recent study by Selig et al. showed that there is a minimum time exposure requirement to receive acceptable DC. They found that 2.6 and 5.7 s of time exposure did not provide sufficient DC, and only 10 s and above gave 47% and above DC (Selig et al., 2015).

The abovementioned studies indicate that increasing the light curing exposure time results in higher overall radiant exposure reaching the RBC layer. Thus, better polymerization can be obtained, especially with a thick composite layer and/or LCU with low irradiance levels.

1.3. Effect of resin increment thickness

Previously, restoration of a deep cavity with a single RBC layer (more than 2.5 mm thickness) was reported to cause a significant reduction in the material properties that may affect its longevity (Sakaguchi et al., 1992). In 1994, Rueggeberg et al. evaluated the effect of filler type, shade, exposure time, and curing radiant exposure on the DC of RBCs (Rueggeberg et al., 1994b). The authors tested RBC samples cured through different thicknesses of already polymerized RBCs for different exposure times (20, 40, 60, or 80 s) with an irradiance level of 800 mW/cm^2. They concluded that the most significant factor in RBCs' DC is the thickness. A thickness of the RBC of more than 2 mm results in significant DC reduction. In addition, Rueggeberg et al., in another study, concluded that, to provide an adequately polymerized RBC, it has to have a 2 mm increment cured for 60 s with irradiance levels of at least 400 mW/cm^2 (Rueggeberg et al., 1994a).

In agreement, Flury et al. (2014) tested the effect of different RBC thicknesses on the Vickers microhardness of different types of RBCs. They reported a reduction in the Vickers microhardness values of the conventional RBCs at a depth of more than 2 mm. Also, Price et al. compared the effect of resin thickness on the microhardness when cured with either PAC or QTH LCUs. The authors reported a significant effect of RBC thickness on the hardness of the RBC. Only 2 mm thickness samples showed equivalent hardness values of top and bottom surfaces at all time intervals using one of the tested LCUs. This indicates adequate DC of the bottom surface of the restoration (Price et al., 2002). Moreover, Rueggeberg et al. studied the effect of different RBC thicknesses on the DC. They prepared specimens of hybrid composite (P-30) in different thicknesses, from 0.5 to 4.5 mm, in 0.5 mm increments. They found a significant reduction of DC in a thickness of more than 2.5 mm in the tested RBC (Rueggeberg and Craig, 1988).

Increasing the RBC restoration thickness results in more curing light absorption and scattering and less light penetration within the layers of the cured material. Therefore, overall curing light energy is reduced with increasing RBC thickness. Accordingly, the DC value of the material is also reduced (Anusavice et al.; Ceballos et al., 2009). Therefore, for cavity preparation exceeding 2 mm, the incremental layering technique is considered a standard of care of RBC placement. This technique reportedly allows sufficient light exposure of the RBC layers and lower polymerization shrinkage (Liebenberg, 1996; Park et al., 2008; Van Ende et al., 2013). On the other hand, the 2 mm increment layering technique is considered time-consuming. Therefore, another category of RBCs has been introduced with composition modifications, which allow adequate DC of the RBCs in a thicker increment (i.e., 4 mm thick). These are called bulk-fill RBCs (Al-Ahdal et al., 2015; Czasch and Ilie, 2013; Jang et al., 2015).

Comparing bulk-fill RBCs with conventional RBCs, El-Damanhoury and Platt evaluated the DC of six RBCs (El-Damanhoury and Platt, 2014), five bulk-fill RBCs (experimental bulk fill) and a microhybrid RBC (Filtek Z250) as a control. RBCs were placed in one increment of 4 mm thickness and light cured for 20 s using LED LCU in standard mode and at an irradiance level of 1000 mW/cm^2. They reported adequate DC of all bulk-fill RBCs at 4 mm RBC thickness. However, Filtek Z250 RBC showed inadequate DC of the bottom surface at 4 mm RBC thickness. Moreover, Garcia et al. studied the impact of RBC thickness on the DC (Garcia et al., 2014). They tested two bulk-fill flowable composites, one standard flowable composite and one regular bulk composite that can be made flowable. A scraping test and Knoop hardness test were used to evaluate the DC of the RBCs, and a higher depth of cure was recorded for the bulk-fill RBCs. Also, Czasch and Ilie compared the DC and microhardness of two bulk-fill RBCs (Czasch and Ilie, 2013). RBCs were placed in one increment, and then light cured for 10, 20, or 40 s. A significant difference was found between both RBC DC and microhardness at all exposure times and depths, resulting from the different compositions of each material. Also, for both RBCs, 4 mm bulk provided a significantly higher DC than 6 mm bulk at all exposure times.

In conclusion, although 2 mm incremental thickness is still the regular standard for RBC increment placement, using bulk-fill allows placement of RBCs in more than 2 mm increments (up to 4 mm) while maintaining an adequate DC. This is due to higher light transmission through the more translucent bulk-fill RBC thickness when compared to conventional RBCs.

1.4. Effect of light curing system

The development of dental light curing units (LCUs) began in the early 1970s when UV-curing units were introduced to polymerize resins (Murray et al., 1981). However, the search was soon on for a better device, because of its limited light resin penetration and potential health risks (Rueggeberg, 2011). Later, visible light curing units were developed, setting the stage for the well-known conventional QTH. The QTH was the unit of choice until the early 2000s. QTH has a quartz bulb filled with halogen, iodine, or bromine gas, and contains a tungsten filament. When electric current passes through the thin tungsten filament, which is surrounded by halogen gas, light is produced. The emitted light is a very powerful white light with a broad spectrum wavelength range (Althoff and Hartung, 2000; Rueggeberg, 1999; Santini et al., 2008). Light is filtered by a filter located inside the LCU to remove most of the useless wavelengths in range during RBC curing (Althoff and Hartung, 2000; Rueggeberg, 1999). Filtered light has a wavelength of 400–500 nm, which is compatible with the most commonly used photoinitiator for curing, camphorquinone (CQ) (Price et al., 2003; Rueggeberg, 1999; Santini et al., 2008). The QTH LCU is a relatively large device with low-energy performance (Kramer et al., 2008). A major disadvantage of the QTH LCU is that the ineffective light produced by the bulb results in an increase in operating temperature (Santini et al., 2008), which limits the lifetime of the bulb (to 100 h) (Kramer et al., 2008). For this reason, fans are required to reduce the temperature (Kramer et al., 2008; Rueggeberg et al., 1994a).

During the era in which QTH was the standard choice, the plasma arc (PAC) LCU was introduced. It also delivers light with a narrower range of wavelengths, which is compatible with CQ (Price et al., 2003). Light polymerization of RBCs using PAC high-intensity light for 3 s provides similar results in terms of DC when using QTH LCU for 30–40 s (Craig and Powers, 2002; Davidson and de Gee, 2000; Jimenez-Planas et al., 2008).

The light-emitting diode (LED) is the newest light source introduced to the dental market and was first developed by Mills and colleagues in 1995 (Mills et al., 1999). LED technology does not use a bulb to produce light but rather junctions of doped semi-conductors. A LED light has a life span of about 10,000 h. The light has a narrower spectrum than halogen lights, 400–500 nm, but is within the range for CQ to polymerize the resin (Mills et al., 1999). The narrow range of light wavelengths emitted by a LED LCU makes it more effective, with less heat generation than a QTH LCU. Therefore, filters are not required in LED LCUs, and the need for fans is minimized. Also, an LED LCU can be used on battery power (cordless LCU) (Althoff and Hartung, 2000; Davidson and de Gee, 2000; Nomura et al., 2002).

New LED LCUs emit lights with two or more different wavelength ranges (polywave LED LCUs). They produce both a shorter violet wavelength and a longer blue wavelength. Violet light is used to activate photoinitiators that are sensitive to light within the range of 350–420 nm wavelength (Cramer et al., 2011; Jandt and Mills, 2013; Leprince et al., 2011; Moszner et al., 2008; Rueggeberg, 2011). However, blue light activates photoinitiators (mainly CQ), with maximum absorbance of light close to 468 nm (Cramer et al., 2011; Jandt and Mills, 2013; Rueggeberg, 2011). Therefore, these polywave LED LCUs are used to activate a wider range of photoinitiators. However, the different positions of each of the light emitters along the same LCU tip could affect the homogeneity of the light output through the light guide tip (Price et al., 2010; Price et al., 2014).

Regarding the effect of light cure unit type on the degree of RBC polymerization, the literature reports different findings. In 2016, Harlow et al. evaluated the light transmission of polywave LED LCUs in violet (350–425 nm) and blue (425–550 nm) spectral ranges through different thicknesses of RBCs. They reported a significant reduction in the light transmission as the thickness of the RBCs increased to more than 2 mm. Reduction in the light output through different RBCs depends on the composition of the material and the spectral range of the light. Greater reduction in the violet light (with the shorter wavelength) was reported. Therefore, the authors recommended higher than 425 nm spectral radiant power when curing highly translucent bulk-fill RBCs at a depth of 4 mm or more (Harlow et al., 2016).

Rueggeberg et al. (2000) investigated the impact of a QTH for 40 s, a plasma arch curing (PAC) unit (for 10 s), and a laser argon curing unit (for 5 s) on RBC hardness. They reported no statistically significant differences in RBC hardness at 2 mm depth after light curing with the different curing units (Rueggeberg et al., 2000). However, AlQahtani et al. (2015) evaluated the effects of three light curing units (QTH, LED, and PAC LCU) with similar radiant exposure (37 J/cm^2). They found a higher DC of tested RBCs when LED and QTH (for 20 and 40 s, respectively) were used, compared to a PAC unit (for 5 s) (AlQahtani et al., 2015). Also, Ceballos et al. compared the curing efficacy of QTH and LED LCUs in curing microhybrid RBC (Filtek Z250) and sub-micron hybrid (Spectrum TPH) RBCs. They reported better curing efficacy using LED LCU for 20 s than with QTH for the same time (Ceballos et al., 2009).

Magalhaes Filho et al. (2016), discussing this factor, stated that physical properties of the RBC are affected mainly by the local power, wavelength, and beam power profile of the LCU used, and concluded that, with the current advanced development of the new LED units and the declining usage of QTH units (mainly owing to a shortage of spare parts and maintenance capacity), the LED unit, preferably its polywave system, is the method of choice to cover a broader range and activate more photoinitiators (Magalhaes Filho et al., 2016).

1.5. Effect of cavity diameter

Owing to the different mesiodistal and buccolingual dimensions of molar and premolar teeth in both maxillary and mandibular jaws, wider diameters of restorations can be found in molar teeth than in premolars (Ash et al., 2003).

Most of the LCU tip shows non-uniformity in light output; some regions of the LCU emit high intensity light, while other areas of the same LCU unit emit a lower irradiances of curing light (Price et al., 2011a). In 2015, Haenel et al. evaluated the effect of irradiance distribution on the local microhardness of RBCs (Haenel et al., 2015). They concluded that the irradiance distributions of different LCUs had a significant effect on both DC and the hardness of the RBCs' surface. Price et al. examined the impact of localized irradiance and spectral distribution inhomogeneities of a polywave LED LCU on the microhardness of four RBCs (Price et al., 2014). The samples were prepared using aluminum rings with 1.2 thickness and 8.2 mm internal diameter. They reported inhomogeneity of local irradiance and spectral emission across the tip of the tested LCU. Also, there was a significant positive relation between the irradiance beam profile values of the LCU and the microhardness of all RBCs when exposed to the light. At 10 s curing time, the overall bottom-to-top surface microhardness value was greater than 80%. However, the periphery of the samples showed a lower microhardness ratio. Additionally, Kostylev et al. reported different polymerization shrinkage configurations of Filtek Supreme Ultra XT (contains CQ photoinitiator only) and Tetric EvoCeram (contains CQ and TPO photoinitiators) samples of 1.22 thickness and 9 mm diameter. RBCs were light polymerized using either a PAC LCU, i.e., Sapphire®, or a polywave LED LCU, i.e., Bluephase Style. Sapphire® was used with three light guide tips: (1) reverse turbo 6.7/11.6 mm light guide, (2) turbo 6.1/2.5 mm light guide, and (3) standard light guide. Non-uniformity in the RBCs' polymerization shrinkage resulted from non-uniform local irradiance of the tested LCUs. Non-uniform local irradiance leads to different rates of polymerization through the surface of the RBC samples (Kostylev et al., 2016).

Therefore, as the cavity diameter increases, the chance of different degrees of polymerization and DC within the same restoration also increases. This could affect the performance of the restoration and limit its longevity. However, Erickson and Barkmeier concluded that less mold dimension results in lower DC, explaining that a narrower mold allows more light absorption by its walls. Thus, it prevents curing light from reaching the RBC surface, resulting in a lower DC than wider diameter molds (Erickson and Barkmeier, 2014). This also means that, with conservative cavity preparation (small diameters), exposure time may need to be increased to adequately cure the RBC increment.

1.6. Effect of cavity location

In some clinical situations, such as in posterior areas, it is impossible to position the LCU tip directly and at 90° over the RBC restoration surface. The location of the RBC restoration, such as on the buccal or lingual surfaces of the second molar, can affect the accessibility and direction of the curing light, which could limit the DC of the cured RBC increment (Price et al., 2010; Price et al., 2000; Shortall et al., 1995). Curing of the restoration in such areas is more difficult and may be done with the LCU tip several millimeters away from the surface of the RBC or at more or less than a 90° angle. With increasing distance between the LCU tip and the RBC surface, light energy reaching the RBC decreases, which leads to a lower value of DC (Maghaireh et al., 2013; Price et al., 2000; Strydom, 2002). In addition, Williams and Johnson stated that the angulation of the LCU tip results in a reduction in light intensity delivered to the RBC surface. Reduction in the radiant exposure is explained by the fact that the circular shape of the light beam changes to an ellipse with greater surface area. A 90° angle of the LCU to the RBC surface is therefore recommended (Williams and Johnson, 1993).

In 2015, Bhatt et al. investigated the effect of the location of the RBC (anterior Class III vs. posterior Class I) on the time needed to deliver radiant exposure of 16 J/cm^2, using a spectroradiometer (Bhatt et al., 2015). RBC restorations were light cured using three different types of LCUs in different modes and with various curing times. Significant differences were found depending on the locations of the LCU and the RBCs. Posterior restoration required more time to deliver 16 J/cm^2 than anterior restoration. This could be due to different configurations, less visibility, and increasing curing distance of the Class I restoration compared to the Class III anterior restoration. In agreement, Mutluay et al. (2014) and Price et al. (2014) reported that an improper position of the LCU in relation to the surface of the RBC restoration affects the light radiant exposure delivered to the restoration. Additionally, Price et al. stated that placement of the LCU at 45° to the surface of the RBC results in a 56% reduction of light radiant exposure (Price et al., 2010).

1.7. Effect of light curing tip distance from RBC surface

Many studies have reported a reduction in radiant exposure of the light from increasing the curing distance between the composite surface and the light cure tip (Beolchi et al., 2015; Prati et al., 1999; Zhu and Platt, 2009). This reduction could be morphological, that is, due to cusp height, cuspal steepness, and cavity depth, forcing the curing tip to be at a distance from the cured RBC surface (Aguiar et al., 2005; Hood, 1991). For example, in deep Class II RBC restorations, the distance from the light guide tip of LCU to the gingival floor of a proximal box can be 6 mm or more (Price et al., 2010; Yearn, 1985). However, in Class I restoration, the cusp height of the restored tooth could result in increasing the distance between the LCU and the last layer of the RBC by 4 mm (Bhatt et al., 2015; Price et al., 2000). Price et al. reported a 50% reduction of light irradiance levels by increasing the curing distance from 0 mm to 6 mm from the LCU and RBC surface, using a standard light guide. This reduction was found to be greater (77% of irradiance levels) when a turbo light guide was used with the same LCU (Price et al., 2000). Price et al. also evaluated the impact of different curing methods on the microhardness of five different RBCs. RBC samples were cured at 2 or 9 mm distance between the tip of the LCU and the RBC surface. The 9 mm distance was selected to represent a clinical scenario of light curing of the first increment RBC layer of deep Class II cavity. They found that increasing the distance from 2 mm to 9 mm between the tip of LCU and the RBC surface resulted in a significant reduction in the surface microhardness of the tested RBCs (Price et al., 2003). Moreover, Aguiar et al. reported a lower microhardness value when cured with 8 mm distance between the light guide tip and the RBC surface than with 2 mm and 4 mm distance (Aguiar et al., 2005). In addition, Thomé et al. reported lower microhardness values of microhybrid and nano-filled RBCs when the distance between the RBC surface and the light cure unit tip was increased from 0 mm to 6 mm and 12 mm (Thome et al., 2007).

These results could be explained by insufficient total energy of light reaching the RBC surface, regardless of the power of the light emitted by different LCUs (Price et al., 2003). So, it is recommended to minimize the distance between the LCU tip and the RBC surface as much as possible, and if such distance cannot be avoided, to consider either extending the curing time or using a higher irradiance level LCU to compensate for the expected reduction in irradiance exposure.

1.8. Effect of curing through different substances

In some clinical conditions, light polymerization of the RBC cannot be achieved directly. However, it can be done through a layer of a substance such as tooth dentin, enamel, RBC layer, ceramic, and/or metal materials. This indirect polymerization of the RBCs through a substance significantly reduces the radiant exposure delivered to the RBC. The amount of reduction depends on the composition, thickness, and translucency of the substance (Davidson-Kaban et al., 1997; Kesrak and

Leevailoj, 2012; Uctasli et al., 1994; Versluis et al., 1998; Watts and Cash, 1994).

Arrais et al. examined the effect of different curing conditions on the DC of dual-cure resin cement system using infrared spectroscopy. They showed a significant reduction in light penetration and thus a reduction in the DC value of resin cements through pre-cured composite compared with curing through a glass slide (Arrais et al., 2008). In addition, an *in vitro* study was carried out to test the impact of different thicknesses of RBC and human dentin on the transmission of curing light. Maximum light energy was measured through a 0.46 mm to 5.85 mm thickness of seven different RBC materials and human dentin, using LCU with either a standard or a turbo light guide. The light energy was found to decrease as the thickness of the RBC and human dentin specimen increased (Price et al., 2000).

Rasetto and colleagues conducted an *in vitro* study to evaluate the effect of different light curing protocols on the DC of light curing resin cement (Variolink II) through three types of porcelain veneer restorations. They found adequate polymerization of Variolink II cement could be achieved in a shorter time using high-intensity LCUs than conventional halogen LCU (Rasetto et al., 2001). Furthermore, Kesrak and Leevailoj investigated the influence of light polymerization through different ceramic disks on the microhardness of resin cements. They found different types and thicknesses of ceramic disks had a significant effect on RBC microhardness. Lower microhardness values of cured resin cement were reported for samples cured through the ceramic with higher opacity. In addition, lower microhardness was observed when cements were cured through an increased thickness of the ceramic (Kesrak and Leevailoj, 2012). This reduction in the microhardness values results from lower light intensity delivered to the cements (Uctasli et al., 1994).

Less light penetration and insufficient light energy reach the RBC material through a ceramic, pre-cured composite, or dentine, leading to a lower polymerization and microhardness value. Therefore, it is suggested that dual-cure resin cement be used for indirect ceramic (with thicknesses more than 1 mm) and composite restoration cementation (Jung et al., 2006). In the case of curing indirect ceramic restorations (in the esthetic zone) within an average of 1.0 mm thicknesses, doubling the curing exposure time as advised by the manufacturers is recommended (AlShaafi et al., 2014).

1.9. Effect of filler type

RBC materials may be classified according to their consistency into packable and flowable RBCs (Ferracane, 2011; Hosoda et al., 1990; Lutz and Phillips, 1983). Flowable RBC has low viscosity, owing to its low filler level or the addition of modifying agents such as surfactants (Bayne et al., 1998). It is used to enhance the adaptation of RBC restoration into the cavity walls and floors with very fine bore syringes. When attempting to restore the function and esthetic of the tooth, packable RBC cannot be inserted into the cavity with a syringe, owing to its high viscosity (Anusavice et al., 2013; Ferracane, 2011).

Monomer and filler type, filler content, and filler and polymer matrix refractive index have an impact on the ability for light to be transmitted throughout the RBC layers (Campbell et al., 1986; Emami et al., 2005). Therefore, it is reported that different RBC compositions, filler size, weight, volume, and filler-to-matrix ratio have a significant effect on the RBCs' DC and microhardness (Atmadja and Bryant, 1990; Barron et al., 1992; Czasch and Ilie, 2013; Scougall-Vilchis et al., 2009)

In 2003, Halvorson et al. concluded that a high DC could be achieved with a lower filler-to-matrix ratio (Halvorson et al., 2003). In agreement, Ferracane et al. compared the DC of three different types of RBC (Macrofill (Prisma-fil), Microfill (Prisma-fine), and conventionally filled (Aurafill)). The specimens were prepared on cylindrical aluminum molds with 4 mm diameter and 5 mm length and light cured for 40 s. They concluded that DC depends significantly on the light penetration capacity through RBC material, which is affected by the filler-resin system. The Microfilled RBC showed the lowest microhardness and DC values, followed by the Macrofilled type. On the other hand, the highest microhardness and DC values were found with Aurafill RBCs (Ferracane et al., 1986). Lower DC and microhardness resulted from differing volume percentages of fillers (i.e., 21% for Prisma-fine, 53% for Prisma-fil, and 62% for Aurafill) and lower light transmission through the RBC layer (Ferracane et al., 1986; Ferracane et al., 1985). Scattering of the light is greater when the RBC filler particle size is almost one half of the curing light wavelength (Prati et al., 1999; Ruyter and Oysaed, 1982; Yap et al., 2003; Yoon et al., 2002).

Ilie et al. and Moszner et al. stated that bulk-fill RBC materials have a better and greater DC than conventional RBCs (Ilie et al., 2013); (Moszner et al., 2008). This was explained by the larger filler size (> 20 μm) composition of the bulk-fill materials, which leads to a lower total filler–matrix interface. This enhances the amount of transmitted curing light and reduces the scattered light, resulting in a higher DC of the larger filler containing RBCs. Furthermore, Jeong et al. evaluated the microhardness of two RBCs (Z250 and Solitaire 2). They found lower microhardness values with Z250 RBC, which could be related to light transmission through RBC layers (Jeong et al., 2009). Additionally, Garcia et al. (2014) studied the impact of RBCs' thickness on the DC. They tested two bulk-fill flowable composites (SureFil SDR Flow and Venus Bulk Fill), one standard flowable (Filtek Supreme Ultra Flowable), and one regular bulk composite that can be made flowable (SonicFill). A scraping test and Knoop hardness test were used to evaluate the DC of the RBCs, and found a higher DC with SonicFill. Also, they found a higher DOC of bulk-fill RBCs than Filtek Supreme Ultra Flowable and SonicFill RBCs using the scraping test. This could be a result of higher translucency, due to the lower filler loading of the bulk-fill RBCs compared to the conventional RBC (Bucuta and Ilie, 2014; Lee, 2008). Thus, more light penetrates through the RBC layers and higher DC of the monomer (Shortall, 2005). Also, Jang et al. (2015) assessed the DC of two bulk-fill composites (Surefil SDR Flow and Venus Bulk Fill), a non-flowable composite (Tetric N-Ceram Bulk Fill), a highly filled flowable composite (G-aenial Universal Flo), and two conventional composites (Tetric Flow and Filtek Supreme Ultra) RBCs. They found adequate polymerization of bulk-fill flowable RBCs (Surefil SDR Flow and Venus Bulk Fill) at 4 mm. However, highly filled flowable (G-aenial Universal Flo), bulk-fill non-flowable (Tetric N-Ceram Bulk Fill), and conventional non-flowable composites (Tetric Flow and Filtek

Supreme Ultra) failed to achieve adequate polymerization at 4 mm sample thickness (Jang et al., 2015). Variations in the microhardness of different RBCs are the result of different compositions of the material (Scougall-Vilchis et al., 2009). A higher DC in Surefil SDR Flow and Venus Bulk Fill could be accounted for by their translucent matrix and incorporation of a functional photoactive group in the methacrylate matrix (Lassila et al., 2012).

Although the literature supports the use of bulk-fill RBCs over conventional types (in both flowable and packable consistencies), further investigations are required to confirm this conclusion, especially when using them in thicker increments (+2 mm) in clinical procedures.

1.10. Effect of temperature on resin DC

Some manufacturers recommend storing RBC material in a dedicated refrigerator. However, decreasing the temperature of the RBC could affect its polymerization reaction (Palin et al., 2014; Price et al., 2011b). An *in vitro* study was carried out by AlShaafi to compare the effect of different polymerization temperatures on the DC and Knoop microhardness of two RBC materials. Samples were divided into two groups according to pre-curing temperature (23 °C or 33 °C), after which all samples were cured with a LED LCU. The DC of the cured material was tested using Attenuated Total Reflectance Fourier Transform Infrared (FT-IR). The microhardness of the top and bottom surfaces of the samples was measured with the Knoop microhardness test. The results showed higher DC and Knoop hardness values in specimens with the higher curing temperature (33 °C) (AlShaafi, 2016). In addition, Price et al. tested the impact of different pre-curing temperatures of Tetric EvoCeram 2 mm thick samples on the DC and surface microhardness values. Specimens were cured for 20 s at 22, 26, 30, or 35 °C. Five minutes after curing, specimens were subjected to FT-IR and Knoop microhardness tests to measure the DC and bottom surface microhardness. These measurements were retaken after 2 h. The study found a higher and faster DC of the RBC with increasing temperature ($p < 0.05$) (Price et al., 2011b).

Increasing the polymerization temperature leads to lower viscosity of the RBC material. This in turn results in greater mobility of monomer molecules within the resin matrix of the RBC and more free radical formation, which results in a higher value of the DC (Palin et al., 2014). Therefore, to enhance the physical properties of clinically used RBCs, preheating through a specific device (e.g., a Calset Warmer unit (AdDent, Inc., Danbury, CT)) is highly recommended.

Conflict of interest

The author has no conflict of interest to declare.

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