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Bulk-Fill Giomers: Effectiveness of Cure and Cross Link Density Associated with Different Light Curing Modes

(Giomer Isi Pukal: Keberkesanan Penyembuhan dan Ketumpatan Pautan Silang Dikaitkan dengan Mod Pengawetan Cahaya Berbeza)

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ABSTRACT

This study investigated the influence of light-curing modes on the effectiveness of cure and cross-link density of restorative (Beautifil Bulk-fill Restorative [BR]) and flowable (Beautifil Bulk-fill Flowable [BF]) giomers. The giomers were placed in black opaque acrylic moulds with cylindrical recesses of 5 mm diameter and 4 mm height, and photo-polymerized with a LED light (Bluephase N) using the following modes: High power (HP) 1200 mW/cm^2 (10 s); Low power (LP) 650 mW/cm^2 (18.5 s); Soft start (SS) 650 mW/cm^2 (5 s) followed by 1200 mW/cm^2 (10 s). The polymerized specimens were stored at 37 °C for 24 h, after which the top and bottom surfaces of the samples were subjected to microhardness testing to assess the effectiveness of cure. The specimens were then conditioned in 75% ethanol-water solution at 37 °C for 24 h and subjected to post-conditioning microhardness testing to determine cross-link density. Mean bottom-to-top hardness ratios and the softening effect (ΔKHN) with ethanol-water solution were computed. Data were analyzed using one-way ANOVA/post-hoc Bonferroni's test and independent samples T-test (α=0.05). The influence of curing modes on the effectiveness of cure and cross-link density were material dependent. Mean pre-conditioning hardness ratios varied from 40.67 to 50.69 for BR and 59.98 to 67.89 for BF with the different curing modes. The most effective cure was achieved with LP and SS for BR and BF, respectively. The lowest cross-link density was observed with LP for both giomers. In conclusion, the effectiveness of cure and cross-link density of bulk-fill giomers are more influenced by the material type than light-curing modes applied.

Keywords: Bulk-fill; cross-link density; giomer; light-curing mode; microhardness

ABSTRAK

Penyelidikan ini mengkaji pengaruh mod pemampatan cahaya terhadap giomer keberkesanan pemampatan dan ketumpatan silang bahan restoratif (Beautifil Bulk-fill Restorative [BR]) dan giomer boleh alir (Beautifil Bulk-fill Flowable [BF]). Giomer diletakkan dalam acuan akrilik opak hitam dengan lekukan silinder berdiameter 5 mm dan ketinggian 4 mm, kemudian dipolimerkan dengan cahaya LED (Bluephase N) menggunakan mod berikut: Kuasa Tinggi (HP) 1200 mW/cm^2 (10 s); Kuasa Rendah (LP) 650 mW/cm^2 (18.5 s); Mula Lembut (SS) 650 mW/cm^2 (5 s) diikuti dengan 1200 mW/cm^2 (10 s). Spesimen yang dipolimerkan disimpan pada suhu 37 °C selama 24 jam, selepas itu permukaan atas dan bawah sampel diuji mikrokeras untuk menilai keberkesanan pemampatan. Spesimen kemudian dikondisikan dalam larutan etanol-air 75% pada suhu 37 °C selama 24 jam dan diuji mikrokeras pasca-kondisi untuk menentukan ketumpatan silang. Nisbah mikrokeras dari bawah ke atas dan kesan lembut (ΔKHN) dengan larutan etanol-air dikira. Data dianalisis menggunakan ANOVA satu hala/ujian Bonferroni pasca-hoc dan ujian sampel bebas T (α=0.05). Pengaruh mod pemampatan terhadap keberkesanan pemampatan dan ketumpatan silang bergantung kepada jenis bahan. Purata nisbah kekerasan pra-kondisi berbeza dari 40.67 hingga 50.69 untuk BR dan 59.98 hingga 67.89 untuk BF dengan mod pemampatan yang berbeza. Pemampatan paling berkesan diperoleh dengan LP dan SS masing-masing untuk BR dan BF. Ketumpatan silang terendah diperhatikan dengan LP untuk kedua-dua giomer. Secara kesimpulannya, keberkesanan pemampatan dan ketumpatan silang giomer isi pukal lebih dipengaruhi oleh jenis bahan berbanding mod pemampatan cahaya yang digunakan.

Kata kunci: Giomer; isi pukal; ketumpatan silang; mikrokeras; mod pemampatan cahaya

INTRODUCTION

Resin-based composites (RBCs) have been widely used as dental restorative materials since their introduction in the 1960s (Bowen 1962). The polymerization shrinkage accompanying the photo-polymerization of RBCs are one of the leading causes for restoration failures, and hitherto, remains a clinical conundrum for many (Carlos et al. 2017). Study by Spajić et al. (2018) indicated that the linear polymerization shrinkage of RBC & giomers varies from 0.80% to 1.65%, with the latter exhibiting lower shrinkage percentage overall. Traditionally, the layering technique involving 2 mm incremental placements of conventional RBCs was employed to mitigate the apparent severity of this problem (Lea et al. 2021). However, this technique proved to be time-consuming with the possibility of air bubble entrapment, contamination, and bond dissociation between the layers (Jang, Park & Hwang 2015; Park et al. 2008). To address this setback, manufacturers developed bulk-fill RBCs that contains novel photoinitiators, special modulators, proprietary resins, unique fillers, and reduced filler loading. Bulk-fill RBCs allow for shorter chairside time with their single placements of up to 4-5 mm thickness (Ilie & Stark 2014; Jang, Park & Hwang 2015). Bulk-fill RBC restorations are reported to have comparable clinical success with conventional RBCs (Veloso et al. 2019). Bulk-fill 'giomers' were recently presented to the dental profession. They are essentially composite resin-glass ionomer hybrid materials that utilize pre-reacted glass ionomer (PRG) fillers. Giomers are capable of releasing and replenishing fluoride in the oral environment while possessing the aesthetic quality and physico-mechanical properties of conventional RBCs (Sunico, Shinkai & Katoh 2005). Their high clinical success rate with regards to physical durability, functional longevity, and low incidence of secondary caries, warrants their use as restorative materials even in stress-bearing areas (Gordan et al. 2014; Sunico, Shinkai & Katoh 2005). However, information about the physical properties of bulk-fill giomers is still limited (Tsujimoto et al. 2017).

Adequate curing of RBCs is crucial to the success of the restorations. Physical properties and clinical durability of RBC restorations are dependent on the amount of polymer conversion or cure achieved (Meng et al. 2017). Residual monomers and reactive components arising from inadequate cure are also cytotoxic and harmful to the dental pulp and surrounding tissues (Meng et al. 2017). This will affect the biocompatibility of restorations and indirectly their longevity (Toh, Yap & Lim 2015). In the ideal situation, the RBCs should be cured throughout the whole thickness, which implies that the top surface microhardness after light polymerization should be equivalent to the bottom surface or $\frac{Bottom\ KHN}{Top\ KHN} = 1(100\%)$. This also means that the photons from the light-curing unit have travelled fully across the thickness of the material and converted the innermost section of the monomers into polymers. However, this is not achievable even in laboratory settings and cure is anticipated to be worse in clinical environments subjected to random uncertainties. Factors such as the material choice, translucency, filler content, and resin composition will have consequential effects on the composite cure as with curing variables such as curing distance and time, as well as curing light source, wavelength, and intensity (Jadhav et al. 2011). Many studies have specified an 80% cure at the bottom surface of RBCs or hardness ratio of 0.8 as the satisfactory cure level (Bouschlicher, Rueggeberg & Wilson 2004; Gan et al. 2018). However, the effectiveness of cure does not provide a full profile of the microscopic polymer branching within the composite structure. Specimens with high or low bottom-to-top hardness ratios may exhibit similar amounts of unreacted C=C bonds as more homogenously polymerized ones. Therefore, the possibility of polymers with identical bottom-to-top hardness ratios but different linearity and cross-link densities need to be accounted for as this will affect the clinical durability of the restoration in the long term (Asmussen & Peutzfeldt 2001).

Like their conventional counterparts, light-curing parameters play an important role in determining the physico-mechanical properties of RBCs (Diab et al. 2021; Gan et al. 2018; Thome et al. 2007; Yap et al. 2004). The influence of light-curing parameters may be heightened considering the application of materials in 4 mm increments. Hypothetically, various light-curing settings/ modes will give rise to different degrees of polymerization shrinkage/contraction stress, cure, and cross-linking as well as polymer structures (Jain et al. 2018; Roy et al. 2018; Spajic et al. 2019). Though the degree of cure can be the same, it was postulated that there are fewer atomic nexuses for polymeric growth with the application of slow start polymerization, which will result in composites with structural matrix dominated by linearity. On the contrary, more atomic nexuses are created with the application of high-intensity irradiance, which causes the internal matrix structure of the composite to be highly cross-linked with an increased amount of interconnecting bonds (Asmussen & Peutzfeldt 2001). Studies investigating the impact of different light-curing modes on bulk-fill giomers are still scarce (Kaya et al. 2018). Hence, this study aimed to determine the influence of light-curing modes on the effectiveness of cure and cross-link density of restorative and flowable bulk-fill giomers. Furthermore, it also compared the effectiveness of cure and cross-link density between the two types of bulk-fill giomers. The null hypotheses were: (a) light-curing modes have no influence on the effectiveness of cure and cross-link density of bulk-fill giomers and (b) there is no difference in effectiveness of cure and cross-link density between restorative and flowable bulk-fill giomers.

MATERIALS AND METHODS

A laboratory study was carried out. The two giomers evaluated were Beautifil Bulk-fill Restorative (BR) and Beautifil Bulk-fill Flowable (BF). Their technical profiles are presented in Table 1. The giomers were placed in a single increment into custom-fabricated moulds with cylindrical recesses of 5 mm diameter and 4 mm height. The giomers were sandwiched between two mylar strips and glass slides and compacted to extrude excess material and ensure flat top and bottom surfaces. The top glass slide was then removed and photo-polymerization was carried out with the top cellulose matrix intact. The distance of the light-curing tip to the surface of the giomers was standardized at 1 mm by using a customized metal jig with an aperture of 10 mm and 1 mm spacers. A polywave light curing unit with their technical profiles presented in Table 2 (Bluephase®N, Ivoclar Vivadent, Schaan, Liechtenstein) was used for photopolymerization with the following modes: High power (HP) 1200 mW/cm^2 (10 s); Low power (LP) 650 mW/cm^2 (18.5 s); Soft-start (SS) 0-650 mW/cm^2 (5 s) followed by 1200 (10 s). The wavelength ranged from 385-515 nm.

Different curing times were applied to ensure similarity in light energy densities between the various light-curing modes. To confirm the consistency of energy output, the irradiance of the curing light was assessed with a radiometer (Bluephase Meter II, Ivoclar Vivadent, Schaan, Liechtenstein) before photopolymerization of the samples. In addition, the light-curing unit (LCU) was systematically checked and re-charged throughout the experiment. After photopolymerization, the samples were removed from their moulds and incubated for 24 h at 37 °C inside a light-proof container at 100% relative humidity. Eight specimens were fabricated for each material-curing mode combination.

EFFECTIVE OF CURE

After the 24 h incubation period, the giomer specimens were subjected to the pre-conditioning Knoops microhardness testing (Shimadzu Corporation, Kyoto, Japan). Three indentations were made on the top and bottom surfaces of each specimen with a 10 gm load for 15 s and the readings were subsequently averaged. The Knoop Hardness Number (KHN) corresponding to each indentation was determined by measuring the dimensions of the indentations using the following formula: KHN = 14.2 × (F/d^2), where F is the test load in kg; and d is the longer diagonal length of an indentation in mm. The effectiveness of cure was established by computing the hardness (ratio) between the top and bottom surfaces of the specimens after photopolymerization with following formula: Bottom KHN/Top KHN where the ideal ratio is around 0.8.

CROSS-LINK DENSITY

The cross-link density was appraised by softening the specimens in alcohol as proposed by Asmussen and

TABLE 1. Technical profiles and manufacturers of the materials evaluated

Material	Manufacturer	Classification	Matrix	Filler Type	Filler Load		Shade
					wt %	vol%	
Beautifil Bulk-fill Restorative (BR)	Shofu Inc., Kyoto, Japan	Bulk-fill restorative giomer	Bis-GMA UDMA Bis-MPEPP TEGDMA (CQ)	S-PRG based on F-Br-Al-Si glass	87	74.5	Universal PN2034
Beautifil Bulk-fill Flowable (BF)		Bulk-fill flowable giomer			73	60	Universal PN2030

Bis-GMA = Bisphenol-A glycidyl methacrylate
UDMA = Urethane Dimethacrylate
Bis-MPEPP= Bisphenol-A polyethoxy-dimethacrylate
CQ= Camphorquinone
TEGDMA= Triethylene glycol dimethacrylate

TABLE 2. Technical profile of the LCU that will be used in the study

Light curing unit	Manufacturer	Type	Range wavelength(s) (nm)	Curing modes	Intensity (mW/cm^2)
Bluephase® N	Ivoclar Vivadent, Schaan, Liechtenstein	Polywave	(385 - 515) nm	High Power	~1200 ± 10%
				Low Power	~650 ± 10%
				Soft Start	~0-650 ± 10%

Peutzfeldt (2001). After pre-conditioning microhardness testing, the specimens were immediately conditioned in 75% ethanol-water solution at 37 °C for 24 h. Post-conditioning hardness was determined as for baseline readings. Mean change in hardness (ΔKHN) was calculated to yield the relative cross-link density values.

SPSS statistical program (version 12.0.1, SPSS Inc., Chicago, USA) was used to analyse the data. Normality testing was done using Shapiro-Wilk test and parametric data analysis was permissible as data was normally distributed. Multi-factorial ANOVA was used to determine the interactions between the independent variables (materials, surfaces, and curing modes) and the dependent variables (KHN. hardness ratios, and ΔKHN). Subsequently, one-way ANOVA followed by Bonferroni's post-hoc tests and independent samples T-test were used to compare curing mode and inter-material differences. All statistical analyses were carried out with a significance level of 0.05.

RESULTS

The top and bottom KHN values of BR and BF with the different curing modes are shown in Table 3 whereas the hardness ratios (%) and ΔKHN values are displayed in Table 4. Statistical comparisons of the various properties across different curing modes and materials are presented in Tables 5 and 6. The analysis of top and bottom KHN values, both pre- and post-conditioning, for BR and BF under three curing modes (HP, LP, and SS) was performed using one-way ANOVA with post-hoc Bonferroni's test ($p < 0.05$), and the results are summarized in Table 5. Table 6 summarizes the comparison of various properties between the two materials for each curing mode, analysed using independent sample t-tests ($p < 0.05$).

The mean hardness ratios pre- and post-conditioning associated with the different curing light modes and materials are illustrated in Figure 1. The mean top KHN of pre-conditioned specimens ranged from 38.2 ± 3.34 to 44.6 ± 2.59 while the mean bottom KHN varied from 16.8 ± 2.97 to 25.8 ± 2.06. For post-conditioned specimens, the mean top KHN ranged from 18.7 ± 1.81 to 26.8 ± 2.40 and mean bottom KHN varied from 16.7 ± 1.16 to 19.7 ± 1.75, respectively. Pre-conditioning hardness ratios ranged from 40.67 ± 8.73% to 67.89 ± 7.79%. Consequently, the top ΔKHN values varied from -21.26 ± 2.4 to -15.95 ± 3.16 and bottom ΔKHN values ranged from -7.03 ± 1.88 to 0.95 ± 4.56.

There were no significant differences in top KHN among the different curing modes for pre-conditioned BR and BF specimens. However, photopolymerization with low power and soft start modes resulted in greater cure at the bottom surfaces for BR. Although no significant differences in the post-conditioned top and bottom KHN was observed for BR, the use of soft start and high-power modes resulted in significantly harder top surfaces and the use of soft start mode led to significantly harder bottom surfaces for BF.

TABLE 3. Hardness (KHN) values of different materials and curing modes: Pre- and post-conditioning

Materials	Curing mode	Top KHN (Pre-conditioning)	Bottom KHN (Pre-conditioning)	Top KHN (Post conditioning)	Bottom KHN (Post conditioning)	Hardness Ratio (Pre-conditioning)	Hardness Ratio (Post conditioning)
Beautifil Bulk-fill Restorative (BR)	High Power (HP)	41.6 (3.47)	16.8 (2.97)	24.7 (1.75)	17.7 (2.40)	40.67 (8.73)	71.92 (9.11)
	Low Power (LP)	44.6 (2.59)	22.6 (1.14)	26.5 (4.16)	19.7 (1.75)	50.69 (3.97)	76.38 (14.19)
	Soft Start (SS)	43.8 (3.25)	20.8 (3.41)	26.8 (2.40)	18.8 (2.11)	47.51 (6.82)	70.78 (11.80)
Beautifil Bulk-fill Flowable (BF)	High Power (HP)	39.2 (1.27)	25.2 (2.15)	21.3 (2.39)	18.3 (1.60)	64.33 (6.24)	86.49 (8.19)
	Low Power (LP)	40.0 (2.82)	23.8 (1.99)	18.7 (1.81)	16.7 (1.16)	59.98 (4.99)	89.89 (6.14)
	Soft Start (SS)	38.2 (3.34)	25.8 (2.06)	22.2 (1.10)	19.0 (1.61)	67.89 (7.79)	85.51 (7.04)

Standard deviations are indicated in parentheses

TABLE 4. Post-Pre-conditioning values ΔKHN of the different materials with different curing modes Standard deviations are indicated in parentheses

Materials	Curing mode	ΔKHN Top hardness	ΔKHN Bottom hardness
Beautifil Bulk-fill Restorative (BR)	High Power (HP)	16.91 (4.27)	-0.95 (4.56)
	Low Power (LP)	18.11 (3.92)	2.8 (1.15)
	Soft Start (SS)	16.99 (3.53)	2.06 (4.59)
Beautifil Bulk-fill Flowable (BF)	High Power (HP)	17.88 (2.46)	6.85 (3.13)
	Low Power (LP)	21.26 (2.40)	7.03 (1.88)
	Soft Start (SS)	15.95 (3.16)	6.76 (2.58)

TABLE 5. Comparison of the various properties between the different curing modes for each material

Material/Properties	Beautifil Bulk-fill Restorative (BR)	Beautifil Bulk-fill Flowable (BF)
Top KHN (Pre-conditioning)	NS	NS
Bottom KHN (Pre-conditioning)	LP, SS > HP	NS
Top KHN (Post conditioning)	NS	SS, HP > LP
Bottom KHN (Post conditioning)	NS	SS > LP
Pre-conditioning hardness ratio %	NS	NS
Top ΔKHN	NS	SS < LP
Bottom ΔKHN	NS	NS

HP, High Power; LP, Low Power; SS, Soft Start. > indicates statistical significance, while NS indicates no statistical significance. Results of one-way ANOVA and post-hoc Bonferroni's ($p<0.05$)

TABLE 6. Comparison of the various properties between the different materials for each curing mode

Curing mode / Properties	High Power (HP)	Low Power (LP)	Soft Start (SS)
Top KHN (Pre-conditioning)	NS	BR > BF	BR > BF
Bottom KHN (Pre-conditioning)	BF > BR	NS	BF > BR
Top KHN (Post conditioning)	BR > BF	BR > BF	BR > BF
Bottom KHN (Post conditioning)	NS	BR > BF	NS
Pre-conditioning hardness ratio %	BF > BR	BF > BR	BF > BR
Top ΔKHN	NS	NS	NS
Bottom ΔKHN	BF > BR	BF > BR	BF > BR

BR, Beautifil Bulk-fill Restorative; BF, Beautifil Bulk-fill Flowable. > indicates statistical significance, while NS indicates no statistical significance. Results of independent sample t-tests ($p<0.05$)

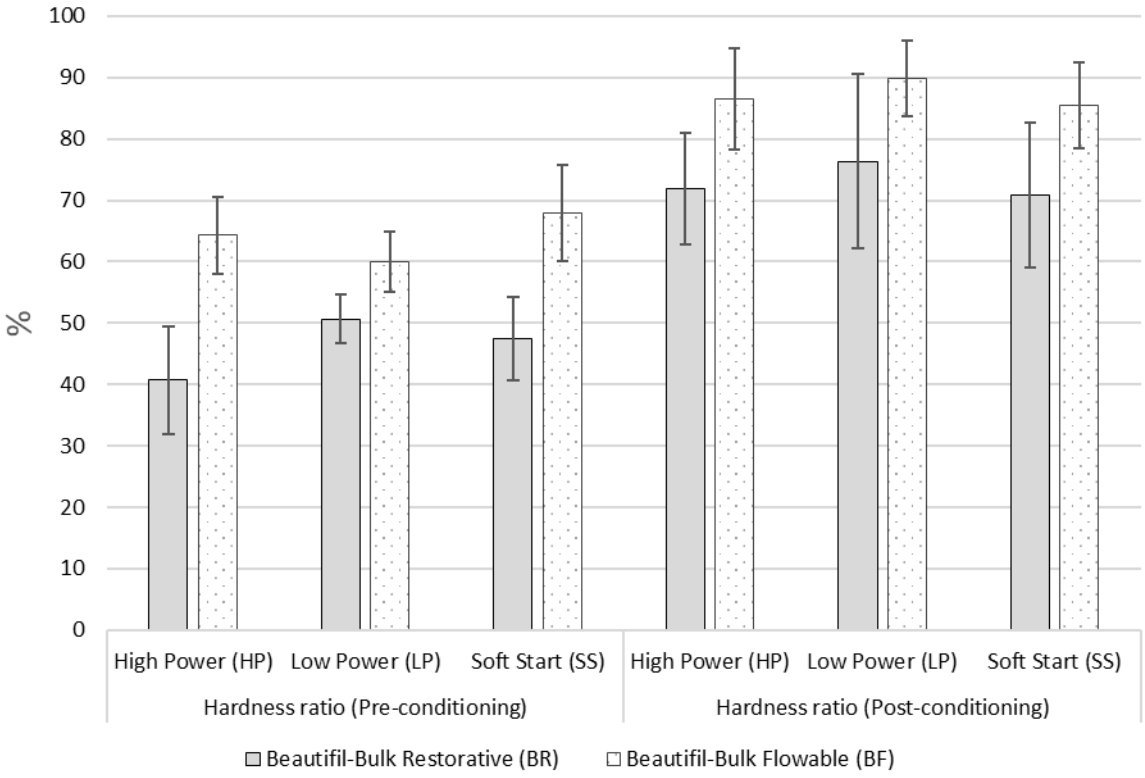

FIGURE 1. Mean hardness ratio post-pre-conditioning associated with the different curing light modes and materials

No significant difference in effectiveness of cure (pre-conditioning hardness ratios) was noted among the different curing modes for both BR and BF. While the ΔKHN of the top surface of BR was not affected by curing modes, curing of BF with soft start mode resulted in significantly lower ΔKHN than with low-power curing. However, the ΔKHN of the bottom surface for both giomers was not influenced by curing modes. In general, BR had significantly higher KHN values for the top surfaces but lower KHN values for the bottom surfaces when compared to BF pre-conditioning. BF exhibited better hardness ratios than BR regardless of curing modes. While no difference in ΔKHN was observed at the top surfaces, BF generally had higher ΔKHN values than BR at the bottom surfaces, signifying lesser cross-linking.

DISCUSSION

This study evaluated two different bulk-fill giomers, namely a high viscosity bulk-fill giomer resin restorative material (BR) and a low viscosity bulk-fill 'flowable base' giomer material (BF). For the flowable giomer, a final layer of conventional RBC is recommended to ensure adequate strength and wear resistance, due to the lower hardness/strength of the flowable giomer with lower filler content (Ruchi et al. 2017). As light-curing modes had some influence on cross-link density, and differences in effectiveness of cure/cross-link densities were observed between the restorative and flowable giomers, both null hypotheses were rejected.

There are two main methods to assess the amount of cure or polymerization of resin-based materials, specifically direct and indirect methods. The most widely used and accurate method to determine the amount of polymerization is the Fourier-transform infrared spectroscopy (FTIR) method. FTIR is a spectroscopic method that calculates the absorption of infrared radiation by the sample material against its wavelength to identify the intrinsic molecular components and structures. This method has been regarded as the gold standard for evaluating the degree the conversion in a given polymer but it requires a high level of intricacies, complex procedural protocols with an extended amount of time in order to accurately determine the conversion rate of the polymer (Mobarak 2009). Indirect methods include visual appraisal, scraping test (ISO 4049), and surface microhardness assessment. These methods are more popular and simpler to execute. However, research objectivity of the visual appraisal method provides no value in this study while the ISO scraping test is deemed unreliable (Yap, Pandya & Toh 2016). Studies have shown that the Knoop hardness technique has an excellent correlation with the FITR method and can be used as an alternative (Asmussen 1982; DeWald & Ferracane 1987). Therefore, after ruling out the other methods available

and taking into consideration the relative simplicity and productivity of the given methods, Knoop hardness technique was ultimately selected to examine the curing effectiveness of the bulk-fill giomers.

Softening upon immersion in ethanol and calculating the difference in microhardness (ΔKHN) was chosen as the surrogate parameter for quantifying cross-link density. As ethanol will disintegrate polymethylmethacrylate, a polymer with greater amount of cross-linking will be dissolved to a lesser extent as compared with another with lower amount of cross-linking. A solution of 75% of ethanol diluted with 15% water was chosen as the conditioning medium as it has been shown to create the greatest softening of BisGMA-based composites (Ayad et al. 2017). To recapitulate, smaller ΔKHN values indicate greater cross-link densities of polymers (Yap et al. 2004). Lower cross-linked composite materials are more vulnerable to water assimilation and breakdown by hydrolysis, ensuing in possible decrease in clinical durability (Indrani et al. 1995; Yap, Teoh & Tan 2000). Hence, it could be indicated that BF giomer should be cured by either high power mode or soft start mode since low power mode yield significantly lower cross-linked end-product. But more evidence is needed to support this.

Camphorquinone (CQ), which has a wide range of absorption of 370 nm to 460 nm was used primarily by both giomers as photoinitiators. In accordance with the manufacturer's claims, these materials can be cured up to 4 mm thickness using LED light-curing unit of 1000 mW/cm^2 or more over 10 s. The irradiance energy output and light energy density were regulated at 12,000 mJ/cm^2 for all curing modes, with the exception of SS mode. The SS mode has a gradually changing curing profile that gave a slightly higher energy output of 13,625 mJ/cm^2. Curing distance was standardized at 1 mm to simulate the minimum clinically feasible distance. Hence, any difference or change in hardness can be attributed primarily to the variance of materials and curing modes.

The effectiveness of cure for both restorative and flowable bulk-fill giomers were not affected by curing modes. Light-curing with LP and SS modes, however, resulted in more cure at the bottom surfaces. This showed that the top surface KHN was less dependent on the type of curing modes then the bottom surfaces. Previous studies on conventional RBC had also suggested that the light intensity had a more profound effect on the bottom surface when compared with the top surface (Lamiaa et al. 2017). The LP mode exhibited the greatest top surface KHN for both BR and BF pre-conditioning. Since light energy output was largely standardized, the relative difference in top KHN might be due to the longer curing time with the LP mode (18.5 s) and greater heat exposure from the LCU (Wahbi et al. 2012). The latter increases the temperature of the material which consequentially improves cure and surface microhardness of composites as demonstrated by Dionysopoulos, Papadopoulos and Koliniotou-Koumpia (2015). RBCs are known to be a poor conductor of heat; therefore, the bottom surface was relatively unaffected by the heat generated (Kamalak et al. 2018). Curing of the bulk-fill flowable giomer with SS mode resulted in significantly better cross-linking at the top surface than with LP mode. Findings were in contrast to those of Yap et al. (2004) on conventional composites. When halogen curing lights were used in SS mode, cross-link density of composites was significantly reduced. Conversely, cross-link density of the bottom surfaces of both giomers was not influenced by curing modes. In our study, the greatest top and bottom ΔKHN values were reported for the LP curing mode for both giomers. Inference can be made that LP mode generated fewer polymeric growth nexus, which results in a more linear polymer structure whereas high-powered cure resulted in the exact opposite, which generated an aggregation of rapidly expanding nexus that manifests in a polymer with higher cross-linking (Asmussen & Peutzfeldt 2001). Thus, bulk-fill giomers cured by LP mode resulted in greater softening by the ethanol solution (lower cross-link density) and may not be the best option as curing mode for bulk-fill giomers.

Flowable RBCs are known to exhibit superior curing effectiveness compared to their restorative counterparts (Flury et al. 2012; Jang, Park & Hwang 2015). This can be attributed to their lower filler content and higher translucency, which facilitate greater light transmission through the material's thickness. Consistent with these findings, our study demonstrated that the flowable giomer (BF) exhibited higher hardness ratios compared to the restorative giomer (BR). However, flowable composites are reported to experience significantly greater polymerization shrinkage, which may compromise their clinical longevity (Lassila et al. 2012).

Despite the observed differences, neither BR nor BF achieved the ideal hardness ratio of 0.8, as suggested by Bouschlicher, Rueggeberg and Wilson (2004). In contrast, this threshold has been achieved with some non-giomer bulk-fill materials (Alshali et al. 2015; Kim et al. 2015). The inclusion of pre-reacted glass (PRG) fillers in giomers may impede light transmission, potentially limiting their depth of cure. Interestingly, BR exhibited generally higher KHN than BF, likely due to its higher filler content (Gan et al. 2018; Yap, Pandya & Toh 2016). These findings underscore the interplay between material composition, light transmission, and mechanical properties in determining the performance of giomer-based restoratives.

While the study by KHN provided valuable insights, its reliance solely on hardness testing limits the scope of its findings. Incorporating additional characterization techniques, such as dynamic mechanical analysis or fracture toughness testing, could offer a more comprehensive understanding of the materials' mechanical performance. Moreover, evaluating factors like polymerization shrinkage and residual stress would enhance the practical relevance by addressing their impact on the clinical longevity of restorations.

In clinical settings, the irradiance of curing lights is further attenuated by challenges such as limited curing access, restricted mouth opening, deep cavities, and the use of interproximal matrices. These conditions exacerbate the already low effectiveness of curing, potentially reducing cross-linking and compromising the lifespan of giomer restorations. To improve polymerization, it may be prudent to cure bulk-fill giomers in smaller increments of 2 mm rather than 4 mm. Expanding the study to include non-giomer-based bulk-fill RBCs and other hybrid materials would provide a broader understanding of the mechanical and clinical performance of these materials under diverse conditions.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions can be made: First, the effectiveness of cure for both restorative and flowable bulk-fill giomers was not influenced by curing modes. Light-curing with low power and soft start modes, however, resulted in more cure at the bottom surfaces. Second, while the cross-link density of the top surface of bulk-fill restorative giomer was not affected by curing modes, curing of the flowable giomer with soft start mode resulted in significantly better cross-linking than with low power. Third, the cross-link density of the bottom surface for both giomers was not influenced by curing modes. Fourth, bulk-fill flowable giomer had greater effectiveness of cure than its restorative counterpart. Fifth, while no difference in cross-linking was observed at the top surface, the flowable giomer was generally less cross-linked than the restorative giomer at the bottom surfaces.

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