Clinical, Cosmetic and Investigational Dentistry

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ORIGINAL RESEARCH

Effect of Polywave and Monowave Light Curing Units on the Microtensile Bond Strength and Failure Types of Different Bulk-Fill Resin Composites: An in vitro Study

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Aim: This study aimed to evaluate the effects of polywave and monowave light-emitting diode curing units on the microtensile bond strength and failure types of three bulk-fill resin composites.

Materials and Methods: This in vitro experimental study was performed on 180 microbars obtained from human third molars and were distributed into 12 groups according to the type of bulk-fill resin composite and the light-curing unit. Third molars were restored using Filtek One Bulk Fill Restorative, Tetric® N-Ceram Bulk Fill, and Opus Bulk Fill resin composites was light-cured with Elipar Deep Cure L and Valo in three modes: standard, high power, and extra power. Subsequently, microtensile analysis was carried out with a universal testing machine and the type of failure with an optical stereomicroscope. For statistical analysis, the Kruskal–Wallis H-test was used, with the Bonferroni post hoc test and Fisher's exact test, considering a significance of $p<0.05$.

Results: There were significant differences in the microtensile bond strength between the Filtek One Bulk Fill restorative and Opus Bulk-Fill ($p = 0.042$) when light was cured with the polywave unit at standard power. On the other hand, the Filtek One Bulk Fill Restorative and Opus Bulk Fill resins showed significant differences in microtensile bond strength when light was cured with the monowave unit compared with the polywave unit ($p<0.05$).

Conclusion: The presence of alternative photoinitiator systems that are more reactive than camphorquinone produced higher microtensile bond strength in Tetric N-Ceram Bulk Fill and Opus Bulk Fill resins when light-cured with a high and standard polywave unit, respectively, compared to Filtek One Bulk Fill resins. Finally, Tetric N-Ceram Bulk Fill and Opus Bulk Fill resins had the highest percentage of mixed failures, while Filtek One Bulk Fill resin had adhesive failures, which was related to its lower microtensile bond strength.

Keywords: dental materials, resin composite, bulk fill, bond strength, monowave, polywave, light curing units

Introduction

The use of resin-based composites in clinical dentistry has become indispensable, offering versatile alternatives to amalgam.[1,2] The most commonly used technique involves incremental placement of restorative materials. However, there are also disadvantages, such as the incorporation of empty spaces, contamination and non-adhesion of layers, difficulty of incremental insertion in smaller preparations, and longer time required for the insertion and polymerization of each increment.[3] For this reason, new products such as bulk-fill resin composites have been introduced in the market.[1,2,4]

Received: 21 February 2024
Accepted: 17 May 2024
Published: 24 May 2024

Bulk-fill resin composites have been developed to reduce operating times and simplify restorative techniques because they can be placed in the cavity preparation and light-cured in a single 4 to 5 mm increment.[4–8] They also contain new and more translucent photoinitiators that allow light transmission to deeper layers.[5–9] Compared to conventional resins, these present reduced polymerization stress and high reactivity to photopolymerization due to changes in the composition and concentration of the filler and/or the organic matrix and also to the presence of stress inhibitors.[1,6,9–11] Shrinkage stresses act along the internal and marginal surfaces and are potentially capable of producing clinical failure due to gap formation, due to dimensional changes of the material at the tooth interface or due to the incidence of occlusal loading.[11,12] That is why, polymerization must be taken into account in clinical practice, since, if photopolymerization does not penetrate to the full depth of the resin, it could compromise its mechanical properties and the integrity of the interface, influencing the durability of the restoration.[1,2,4] Microtensile strength is one of the least investigated mechanical properties in these composites.[8]

The microtensile bond strength test (μTBS) has some advantages, such as the ability to investigate bond strength in small areas below 1 mm^2.[6,13] This makes it a more versatile alternative because multiple samples can be obtained from a single tooth, allowing for more assertive studies and better substrate control.[6,13,14] In addition, the clinical results of the microtensile bond strength evaluation were more reliable than those of the microshear bond strength testing.[15,16] The rationale for evaluating microtensile bond strength is that the stronger the bond between the tooth and the biomaterial, the greater the resistance of the restoration to stresses imposed by resin polymerization and oral function.[6,13,14] Therefore, inadequate polymerization may result in reduced biocompatibility owing to the release of unreacted monomers, decreased mechanical properties, and decreased color stability.[5,17,18]

Parallel to the advances in resin composites, there have also been improvements in the light-curing units.[19–21] Recent polywave light-emitting diode (LED) devices have broader-spectrum light emission peaks, which are used to activate alternative photoinitiators. Traditional single-emission-peak LEDs, called monowaves, are sufficient to activate the photoinitiator camphorquinone[1,13,20,21] but cannot provide adequate curing for resin composites containing alternative photoinitiators.[20,21] The demand for quick solutions has led lamp manufacturers to shorten the curing time with the prerequisite of a high radiant output of photopolymerization devices of 3000 mW/cm^2 or higher.[22,23] Modern LED curing units are equipped with multiple curing modes: standard, high-power mode, etc. and these modalities can be continuous or intermittent, depending on the manufacturer. However, the concept of high irradiance has been strongly criticized, since the type of photocuring unit, intensity, exposure time, wavelength, temperature and photoinitiator, among others, are factors that must be considered so as not to affect adequate polymerization, which can compromise mechanical properties.[1,8,9]

Light curing of bulk-fill resin composites using extremely high irradiance is based on the premise that adequate curing can be achieved using short exposure times. This would increase the simplicity and efficiency of dental treatments by reducing the procedure time and would be of economic benefit, as well as reducing the risk of fluid contamination.[22–25] However, recent studies have revealed that rapid curing with high-irradiance light can create large shrinkage stresses within the composite material and at the dentin-composite adhesive interface, which can affect the bond strength.[25–27]

In view of the above, the null hypothesis of this research was that there are no significant differences in the microtensile bond strength and failure types of bulk fill resin composites when light cured with monowave and polywave LED units. Therefore, the aim was to assess the effect of polywave and monowave LED curing units on the microtensile bond strength and failure types of three bulk fill resin composites.

Materials and Methods

Type of Study and Delimitation

This in vitro experimental study was conducted at the Faculty of Stomatology of the Universidad Privada Antenor Orrego and at the High Technology Laboratory Certificate, Lima, Peru, from August to November 2022. In addition, this study considered a (checklist for reporting in vitro Studies) guideline.[28]

Sample Calculation and Selection

The total sample size (n = 180) was calculated based on the data obtained in a previous pilot study with five sample units per group. The formula for analysis of variance was applied in the statistical software G*Power version 3.1.9.7, considering a significance level (α) = 0.05 and a statistical power (1-β) = 0.80, with an effect size of 0.32 with 12 groups. There were randomly divided into 12 groups (n = 15 samples per group) [Figure 1] according to the type of adhesive restorative system, light-curing unit, and curing mode used. All treatment procedures were performed by the same operator.

Sample Characteristics and Preparation

Third molars with the following characteristics were included: extracted molars 3 months before the experiment, obtained from a specific age range (20 to 30 years), upper or lower molars extracted for orthodontic purposes, without dental caries, presence of cracks or fractures and previous fillings. The remaining soft tissue or bacterial plaque was removed using dental ultrasound (UDS J; Woodpecker, Guilin, Guangxi, China). The teeth were then rinsed and immersed in a 1% t-chloramine solution (Millipore, Supelco, Lima, Peru) for one week for disinfection. They were then placed in a container with distilled water at 4°C for maintenance, with water replacement every seven days. Finally, before sectioning the occlusal third of the molar teeth using a micromotor (DREMEL® 3000 Series, Mt. Prospect, Illinois, USA) with a water-cooled diamond cutting disc, all the teeth were placed in saline solution for 24 h at 37°C ± 2°C[29] [Figure 2].

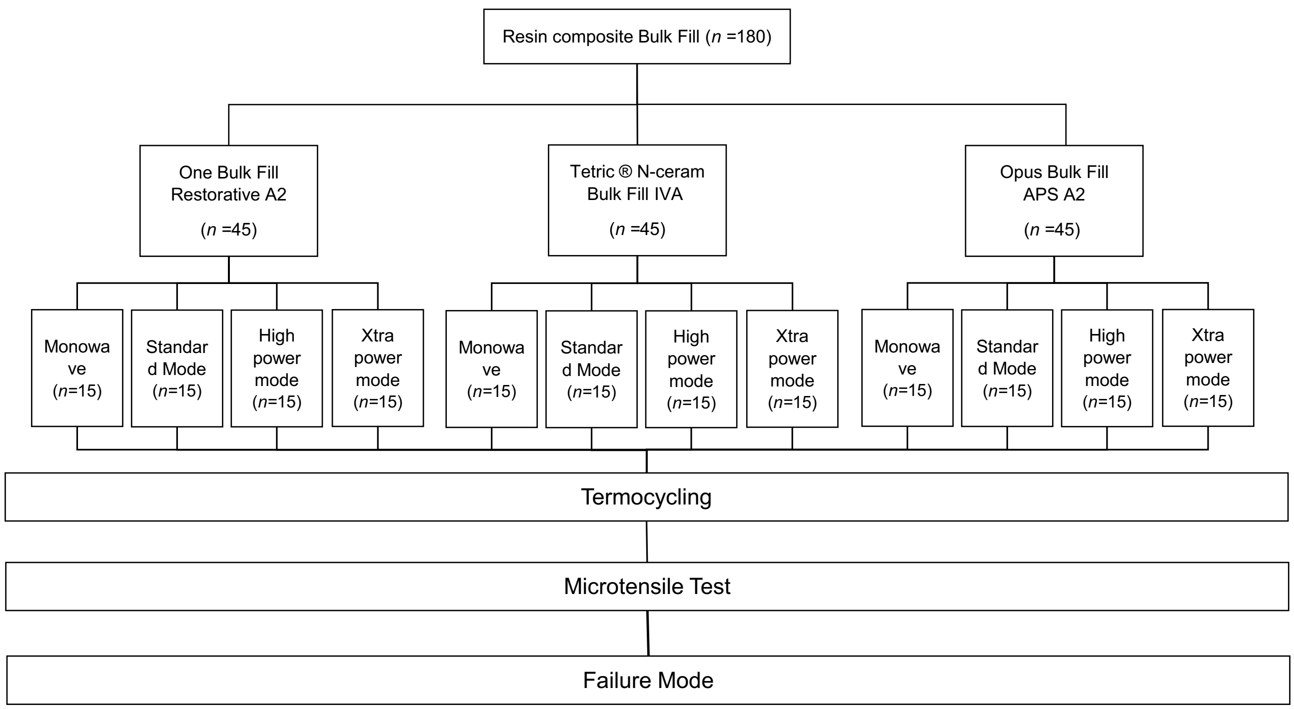

Figure 1 Random distribution of groups by type of Bulk Fill resin composite and light curing units and modes.

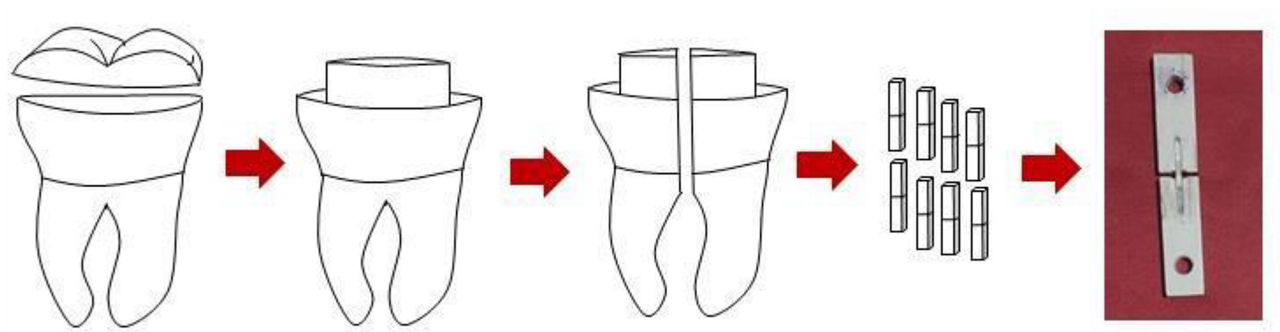

Figure 2 Preparation of microbars for microtensile bond strength testing.

For conditioning, etching acids were used: 37% Eco- Etch® (Ivoclar Vivadent, Schaan, Liechtenstein), Condac 37 (FGM, Santa Catarina, Brazil), ScotchbondTM Etchant (3M ESPE, Saint Paul, USA), performing acid etching for 15 seconds, then washed with water for 10 seconds and dried the excess moisture with cotton. Ambar (FGM), Tetric® N- Bond (Ivoclar Vivadent), Adper TM Single Bond 2 (3M ESPE), were applied on samples, evaporating the solvent with gentle air flow for 3 seconds and light cured with an LED lamp at an intensity of 1200 mW/cm2 for 20 seconds. One bulk-fill restorative A2 (3M ESPE), Tetric® N-Ceram Bulk Fill IVA (Ivoclar Vivadent), and Opus Bulk Fill APS (Advanced Polymerization System) (FGM) A2 resin composites were placed on the dentin at a height of 4 mm. Each resin composite was placed with its respective adhesive system and light-cured with Elipar Deep cure L (3M ESPE, Saint Paul, USA) at 1470 mW/cm^2 for 20s and Valo (Ultradent Products, South Jordan, USA) in three modes: standard mode (1000 mW/cm^2 for 20s), high-power mode (1400 mW/cm^2) for 12s, and extra power mode (3200 mW/cm^2 for 6 s). The curing modes and durations selected for our investigation are consistent with those recommended by the Valo manufacturer.

The curing times and number of cycles were based on the manufacturer's recommendations for optimal results using an LED polywave curing unit.[30] Two light-curing units were tested using a radiometer (Woodpecker® LM-1; Woodpecker, Guilin, Guangxi, China). The latter device was tested in three curing modes (standard, high-power, and extra power modes). [Table 1 and Table 2].

Table 1 Technical Profile of Products Used

Product	Composition	Filler % (wt-vol)	Manufacturer	Lot
One Bulk Fill Restorative A2	Marix: AUDMA, UDMA, 1,12-dodecaeno-DMA Filler: ytterbium trifluoride f., non-aggl./non-aggr. silica f, zirconia, aggr. zirconia/silica cluster f.	76.5 wt% 58.5 vol%	FGM Dental Products; Joinville, SC, Brazil	NE58805
Tetric® N-Ceram Bulk Fill IVA	Matrix: bis-GMA, bis-EMA, UDMA Filler: barium silicate alumino glass, "isofiller" (prepolymer, glass and ytterbium fluoride), ytterbium fluoride and mixed oxides	76 wt% 54 vol%	Ivoclar Vivadent, Schaan, Liechtenstein	Z02TBZ
Opus Bulk Fill APS A2	Matrix: bis-GMA, UDMA Filler: Nanofiller Photoinitiating-Advanced Polymerization System (APS). Inorganic load of silanized silicon dioxide (silica), barium glass aluminosilicate	76.5 wt% 58.4 vol%	FGM, Santa Catarina, Brasil	010221
Condac 37	37% phosphoric acid gel, dye, deionized water, thickener	-	FGM Dental Products; Joinville, SC, Brazil	100122
Scotchbond™ Etchant	35% phosphoric acid, water, poly (vinyl alcohol), amorphous silica thickener	-	3M, ESPE, St. Paul, MN, USA	NE33244
Eco- Etch®	37% phosphoric acid, water, pigments, silicon dioxide	-	Ivoclar Vivadent, Schaan, Liechtenstein	Z02RR3
Ambar	UDMA, HEMA, methacrylate acidic monomers, methacrylate hydrophilic monomers, silanized silicon dioxide, camphorquinone, 4-EDAMB, etanol	-	FGM Dental Products; Joinville, SC, Brazil	060122
Adper ™ Single Bond 2	Bis-GMA, polyalkenoic acid co-polymer, dimethacrylates, HEMA, photoinitiators, ethanol, water, nanofiller particles	-	3M, ESPE, St. Paul, MN, USA	NC85092
Tetric® N- Bond	BISGMA, 2-hydroxyethyl methacrylate, phosphonic acid acrylate, Urethane Dimethacrylate	-	Ivoclar Vivadent, Schaan, Liechtenstein	Z030FN

Table 2 Light Curing Units and Curing Mode Used in This Study

Light Curing Units	Type	Curing Modes	Spectral Range (nm)	Manufacturer
Elipar™ DeepCure-L	Monowave	1470 mW/cm^2 × 20s	430–480	3M, ESPE, St. Paul, MN, USA
VALO	Polywave	Standard mode: 1000 mW/cm^2 × 20s High power mode: 1400 mW/cm^2 × 12s Extra power mode: 3200 mW/cm^2 × 6 s	395–480	Ultradent Products, South Jordan, EE. UU.

Subsequently, 10,000 thermocycles between 5±2°C and 55±2°C[5,13,30,31] were applied to all samples. Then, the microbars were cut. Horizontal and vertical cuts were performed using a water-cooled diamond cutting disc at a low speed, and the disc was changed every 5 cuts.[29] The dimensions of the microbars were 1×1 × 8 mm,[29,30,32] with n = 15 per group. The measurements were performed using a digital calliper (Mitutoyo, Kawasaki, Kanagawa, Japan).

Microtensile Testing

Once 180 samples were obtained, they were placed in distilled water[7,15] for 24 h at room temperature before the microtensile test. Width and depth of all specimens were measured with a digital caliper prior to testing. The microbar was attached to a custom-made microtensile fixture using cyanoacrylate glue. Specimen was positioned parallel to the long axis of the jig and cement layer was at the middle of testing device gap in order to minimize bending stresses. The test was performed on a universal testing machine (CMT-5L Liangong, Shandong, China) with digital software (Smart Test) at a crosshead speed of 0.5 mm/min.[6,13,14,27,30] The µTBS values obtained after the test were analysed in megapascals (MPa) [Figure 3].

Failure Type

To assess the type of failure, the fractured samples were examined using a Leica EZ4 optical stereomicroscope (Leica Microsystems Inc., Concord, ON, Canada). Joint failure was classified as adhesive, cohesive, or mixed [Figure 4].

Statistical analysis

The collected data were stored in a Microsoft Excel 2019® spreadsheet and subsequently imported into the SPSS program (Statistical Package for the Social Sciences Inc. IBM, NY, USA) version 28.0. For descriptive analysis, measures of central tendency, such as mean and median, and measures of dispersion, such as standard deviation and interquartile range, were used as quantitative variables. Relative and absolute frequencies were used as qualitative variables. For the comparative analysis of adhesive strength, the Shapiro–Wilk normality test and Levene's

Figure 3 Microtensile bond strength testing.

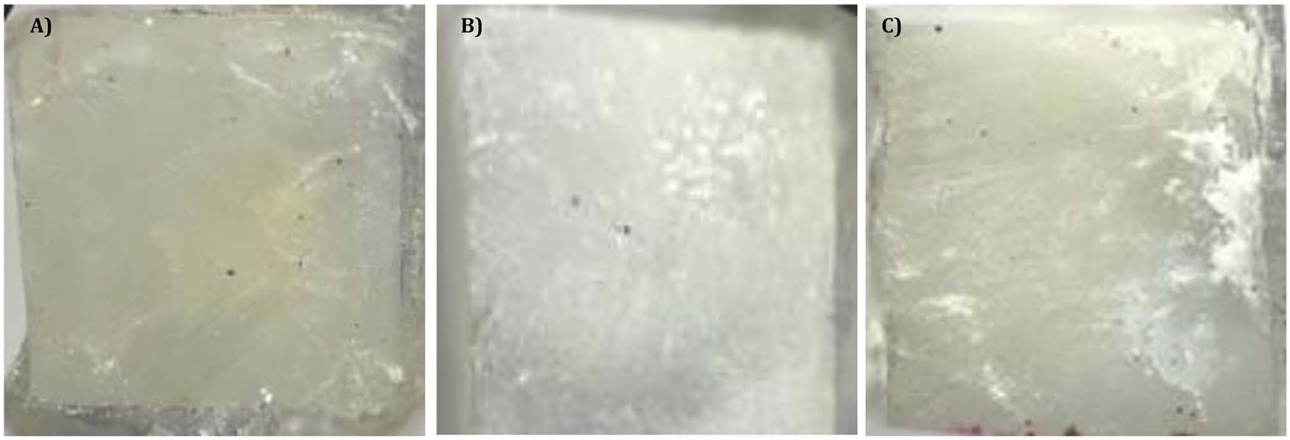

Figure 4 Stereomicroscopy images showing bond failures.
Notes: (**A**) Adhesive failure at the dentin/resin interface; (**B**) Cohesive failure within the composite; and (**C**) Mixed failure.

homoscedasticity test were performed. Based on these results, we used the non-parametric Kruskal–Wallis test with Bonferroni post-hoc test. On the other hand, Fisher's exact test was used to evaluate the association of the type of failure with the light-curing unit. All statistical tests were set at a significance level of $p<0.05$.

Ethical Considerations

This study adhered to the ethical principles for medical research with human beings in the Declaration of Helsinki.[18,28] This study was approved by the Ethics and Research Committee of the Faculty of Stomatology of the Universidad Privada Antenor Orrego (official letter no. 0360–2022-D-EPG-UPAO). The teeth used were voluntarily donated and extracted for orthodontic or prosthetic reasons with prior informed consent.

Results

When comparing the microtensile bond strengths (MPa) of the three bulk-fill resin composites, significant differences were observed between the Filtek One Bulk Fill and Opus Bulk Fill (p = 0.042) when light was cured with the polywave unit at standard power. Significant differences were also observed when comparing the Tetric N-Ceram Bulk Fill with the Filtek One Bulk Fill (p = 0.011) and Opus Bulk Fill (p = 0.047) when the light was cured with a polywave unit at high power. However, there was no significant difference in the microtensile bond strength (MPa) when using both the monowave curing unit (p = 0.067) and polywave curing unit at extra power (p = 0.567) for the three bulk-fill resin composites [Table 3].

Table 3 Comparison of the Microtensile Bond Strength (MPa) of Three Bulk Fill Resin Composites According to Type of Light Curing Used

Light Curing Unit	Resin Composite	n	Mean	SD	95% CI		Median	IQR	*p	Average Range**	**p
					LL	UL					
Monowave	FO-BF	15	9.27	5.09	6.45	12.09	7.95	5.92	0.106	28.37	0.067
	O-BF	15	7.09	2.34	5.79	8.38	6.2	3.74	0.034	23.40	
	TNC-BF	15	5.47	1.76	4.50	6.44	5.9	2.15	0.077	17.23	
Poliwave Standard	FO-BF	15	2.88	1.2	2.21	3.54	2.69^{A}	2.11	0.364	16.03	0.036
	O-BF	15	4.24	1.67	3.32	5.17	3.58^{B}	1.49	0.041	27.80	
	TNC-BF	15	3.97	1.71	3.02	4.92	$3.42^{A,B}$	1.46	0.003	25.17	

(*Continued*)

Table 3 (Continued).

Light Curing Unit	Resin Composite	n	Mean	SD	95% CI		Median	IQR	*p	Average Range**	**p
					LL	UL					
Poliwave High	FO-BF	15	4.59	1.95	3.51	5.67	3.61^{A}	2.52	0.016	17.60	0.008
	O-BF	15	4.41	1.21	3.74	5.08	4.39^{A}	1.14	0.188	19.90	
	TNC-BF	15	6.36	2.09	5.21	7.52	6.02^{B}	4.11	0.204	31.50	
Poliwave Extra	FO-BF	15	4.17	1.61	3.28	5.06	3.64	2.09	0.123	20.87	0.567
	O-BF	15	5.03	2.57	3.61	6.45	4.35	4.18	0.239	25.83	
	TNC-BF	15	4.37	1.7	3.43	5.32	3.58	2.26	0.036	22.30	

Notes: n, sample size. *Based on Shapiro Wilk Normality Test (*p>0.05, normal distribution); **Based on Kruskal Wallis H (**p<0.05, significant differences). A, B: Different letters in the median column indicate significant differences (p<0.05) according to Bonferroni's post hoc.
Abbreviations: SD, standard deviation; CI: Confidence Interval; LL, Lower Limit; UL, Upper Limit; IQR, interquartile range; FO-BF, Filtek One Bulk Fill; O-BF, Opus Bulk Fill APS; TNC-BF, Tetric N-Ceram Bulk-fill.

When comparing the microtensile bond strength (MPa) with different types of light curing, it was observed that the Filtek One Bulk Fill showed significant differences when the light was cured with the monowave unit versus the polywave unit with standard power ($p < 0.001$) and extra power ($p = 0.018$). Similarly, there were significant differences in the Opus Bulk Fill when the light was cured with the monowave unit versus the polywave unit with standard power ($p = 0.001$), high power ($p = 0.008$), and extra power ($p = 0.045$). Finally, significant differences were observed in the Tetric N-Ceram Bulk Fill when light was cured with the polywave unit at standard power versus the same unit at high power ($p = 0.006$) [Table 4].

There was a significant association between the power of the curing unit and the type of failure for the Filtek One Bulk Fill composite resin, as it was observed that the type of failure of this resin was predominantly adhesive failure when it was light-cured with standard and high-power polywave units. However, when the composite resin was light-cured with a monowave unit and an extra power polywave unit, mixed failures were predominant. However, there was no significant association between the failure type and light-curing unit strength in the Opus Bulk Fill ($p = 0.963$) and Tetric N-Ceram Bulk Fill ($p = 0.998$) composite resins, as both showed predominantly mixed failure, regardless of whether they were light-cured with a monowave or polywave unit [Table 5].

Table 4 Comparison of Microtensile Bond Strength (MPa) with Different Types of Light Curing According to the Bulk Fill Resin Composite Used

Resin Composite	Light Curing Unit	n	Mean	SD	95% CI		Median	IQR	Average Range*	*p
					LL	UL				
FO-BF	Monowave	15	9.27	5.09	6.45	12.09	7.95^{B}	5.92	47.33	<0.001
	Standard	15	2.88	1.2	2.21	3.54	2.69^{A}	2.11	15.57	
	High	15	4.59	1.95	3.51	5.67	3.61^{A,B}	2.52	30.67	
	Extra	15	4.17	1.61	3.28	5.06	3.64^{A}	2.09	28.43	
O-BF	Monowave	15	7.09	2.34	5.79	8.38	6.20^{B}	3.74	45.9	<0.001
	Standard	15	4.24	1.67	3.32	5.17	3.58^{A}	1.49	21.8	
	High	15	4.41	1.21	3.74	5.08	4.39^{A}	1.14	25.43	
	Extra	15	5.03	2.57	3.61	6.45	4.35^{A}	4.18	28.87	
TNC-BF	Monowave	15	5.47	1.76	4.50	6.44	5.90^{A,B}	2.15	36.33	0.002
	Standard	15	3.97	1.71	3.02	4.92	3.42^{A}	1.46	20.1	
	High	15	6.36	2.09	5.21	7.52	6.02^{B}	4.11	41.13	
	Extra	15	4.37	1.7	3.43	5.32	3.58^{A,B}	2.26	24.43	

Notes: n, sample size; *Based on Kruskal Wallis H (*p<0.05, significant differences). ^{A,B}Different letters in the median column indicate significant differences (p<0.05) according to Bonferroni's post hoc.
Abbreviations: SD, standard deviation; CI, Confidence Interval; LL, Lower Limit; UL, Upper Limit; IQR, interquartile range; FO-BF, Filtek One Bulk Fill; O-BF, Opus Bulk Fill APS; TNC-BF, Tetric N-Ceram Bulk-fill.

Table 5 Comparison of Failure Types with Different Types of Light Curing According to the Bulk Fill Resin Composite Used

Resin Composite	Light Curing Unit	n	Failure Types			*Mode	p**
			Adhesive	Cohesive	Mixed		
			f (%)	f (%)	f (%)		
FO-BF	Monowave	15	4 (26.7)	1 (6.7)	10 (66.7)	Mixed	<0.001**
	Standard	15	13 (86.7)	0 (0.0)	2 (13.3)	Adhesive	
	High	15	13 (86.7)	1 (6.7)	1 (6.7)	Adhesive	
	Extra	15	5 (33.3)	1 (6.7)	9 (60.0)	Mixed	
O-BF	Monowave	15	2 (13.3)	2 (13.3)	11 (73.3)	Mixed	0.963
	Standard	15	3 (20.0)	1 (6.7)	11 (73.3)	Mixed	
	High	15	1 (6.7)	3 (20.0)	11 (73.3)	Mixed	
	Extra	15	2 (13.3)	2 (13.3)	11 (73.3)	Mixed	
TNC-BF	Monowave	15	2 (13.3)	3 (20.0)	10 (66.7)	Mixed	0.998
	Standard	15	2 (13.3)	2 (13.3)	11 (73.3)	Mixed	
	High	15	2 (13.3)	3 (20.0)	10 (66.7)	Mixed	
	Extra	15	2 (13.3)	4 (26.7)	9 (60.0)	Mixed	

Notes: n, sample size; f, absolute frequency; %, relative frequency. *The mode was used to observe the predominance of failure types. **Based on Fisher's exact test (p<0.05, significant association).
Abbreviations: FO-BF, Filtek One Bulk Fill; O-BF, Opus Bulk Fill APS; TNC-BF, Tetric N-Ceram Bulk-fill.

Discussion

The microtensile bond strength of the three bulk-fill resin composites was evaluated because the formation of an adhesive bond with the tooth structure is the most important factor for the long-term retention of resin composite restorations.[6] The null hypothesis was rejected because significant differences were observed in the microtensile bond strength and failure types of the bulk-fill resin composites when the light was cured with monowave and polywave units.

Monowave LED light-curing units (LCU) have a visible range of 445–480 nm, which coincides with the absorption spectrum of camphorquinone (CQ) (430–500 nm). However, under these wavelengths, alternative photoinitiators such as Lucirin TPO, bisacylphosphine oxide (BAPO), monoacylphosphine oxide (MAPO), and ivocerin are not activated efficiently, resulting in a lower degree of conversion.[15,20,27,33] Manufacturers have introduced polywave LCUs to efficiently cure a wide range of composites using alternative photoinitiators. These devices have LED chips that emit light over a wider range from 380 to 550 nm, allowing the activation of different photoinitiators more efficiently.[20,33]

The effectiveness of polymerization in light-activated materials is related to the enhanced mechanical behaviour of the resin composites and depends directly on parameters specific to the polymerization reaction, such as the degree of monomer-to-polymer conversion and rate of polymerization.[2,5] In this sense, the degree of conversion depends on the type of monomers present in the organic matrix, as well as on the number of radicals generated in the activation stage of the polymerization reaction, thus becoming a crucial factor in determining the mechanical properties of the materials and their biocompatibility.[2,5,8,24,25]

The values obtained for the three bulk-fill resin composites cured with a monowave unit were not surprising, because these products were specifically designed for curing using the conventional protocol. However, when comparing the adhesive strength of the three restorative materials with polywave unit under standard power (1000 mW/cm^2 × 20s), significantly lower adhesive strength was observed in Filtek One Bulk Fill compared to Tetric N-Ceram Bulk and Opus Bulk Fill. Significant differences were also observed when light-cured the three bulk-fill resin composites with the high-power polywave unit (1400 mW/cm^2 × 12s), Tetric N-Ceram Bulk Fill, and Opus Bulk Fill, which showed the highest adhesive strength.

These findings disagree with those of Mandava et al[6] and Makhdoom et al[15] because these studies used Filtek Bulk Fill Posterior resin composites of very similar composition to Filtek One Bulk Fill.[6,15] The authors reported superior properties due to the presence of aromatic dimethacrylate (AUD-MA) and additional fragmentation molecules (AFM) in its composition. The inclusion of these monomers in the polymerization mixture allows the network to reorganise and adapt during and/or after light-curing.

The results obtained in the present study are in agreement with those obtained by Tsuzuki et al,[1] Varshney et al,[33] Siagian et al,[34] and Alavi et al,[35] who reported that LED polywaves allow for a higher degree of conversion in composites containing camphorquinone (CQ) associated with alternative photoinitiators requiring shorter wavelengths. This was the case for the Opus Bulk Fill and Tetric N-Ceram Bulk Fill which presented higher bond strength values, probably because of the presence of alternative photoinitiators intended to enhance light-curing. Opus Bulk Fill works with a new advanced polymerization system (APS) technology that reduces the amount of camphorquinone by incorporating other types of initiators and manufacturers' secret alternative co-initiators that amplify the polymerization capacity and increase both the degree of conversion and the depth of cure.[36–38] The Tetric N-Ceram Bulk Fill also features ivocerin (a derivative of dibenzoyl germanium) and monoacylphosphine oxide (TPO). Both photoinitiators were stimulated by different wavelengths, which improved their mechanical properties.[5,14,37,39] The higher absorption of visible light by these photoinitiators could have contributed to their greater depth of cure. This did not occur with Filtek One Bulk Fill because it contained only CQ. Another argument in favour of Tetric N-Ceram and Opus Bulk Fill is that the former contains alternative photoinitiators, such as Ivocerin and Lucirin, and the latter has an APS system. These are activated through a Norrish type-I chemical reaction which makes them more effective for high-intensity curing than traditional camphorquinone photoinitiator systems.[8,22,23] Some photoinitiators can be classified as Norrish type I, meaning they have low-energy bonds that can break upon exposure to light to generate free radicals. While the others are Norrish type II, this classification is due to the need to combine with a reducing agent to generate free radicals and initiate the polymerization reaction, as is the case with camphorquinone.[8,20,27] The remarkable variation in filler particle size and monomer blends among the tested composites must be considered when analyzing parameters related to polymerization.[25,27]

Interestingly, all the resin composites used in the present study that contained additional photoinitiators achieved higher bond strength values when light-cured with polywave LCU, which is in agreement with the results reported by Derchi et al,[21] Alavi et al,[35] and Araujo et al.[39] These authors demonstrated that mono-wave LCU was more effective in curing resin composites with camphorquinone as the photoinitiator.[21,35,39] They also stated that polywave light, owing to the incorporation of violet light, reduces the blue light emission in composites with alternative photoinitiators, causing a lower activation of camphorquinone and showing a better degree of conversion compared to monowave LED curing. They concluded that alternative photoinitiators play a predominant role in allowing short curing times with an adequate depth of cure.[8,21,27,35,39]

There is controversy over high irradiance levels as they can produce greater polymerization contraction and internal stress within the bonding interface, but also low irradiance could cause insufficient polymerization of the composite resin, with high levels of residual monomer and this can reduce the mechanical properties of the final restoration, which is why new curing methods are being suggested.[24,40] The assumption that an increase in irradiance and a decrease in curing time would lead to poor mechanical properties[5,24] is not accurate because the properties of the resin composite after light curing depend not only on the curing protocols, but also on the intrinsic characteristics of the material, such as the type of monomer present in the organic matrix, photoinitiator, monomer viscosity, and mobility of the radicals. Therefore, such reasoning cannot be considered a general rule.[5,8,24,25] The composition of the bulk-fill resin composite and the depth of cure are factors that should be considered because they may influence the mechanical properties of the composite.[33,37] It is also important to consider the large shrinkage stresses that are generated within the resin composite and at the dentin-composite adhesive interface because they can affect the bond strength.[25,41,42] If the stress resulting from polymerization contraction exceeds the bond strength of the composite to the cavity walls, failures may occur at the marginal bonds. However, if the bonding interface resists and remains intact, residual stress could be transferred to adjacent tooth structures, possibly resulting in fractures of the enamel or dentin.[40]

However, in the samples of the Filtek One Bulk Fill resin composite, a better bond strength was observed with the monowave unit as opposed to the polywave unit with standard and extra power. This could be due to the fact that Filtek One Bulk Fill was the most filled material, containing 58.5% by volume. Contreras et al[20] reported that a high filler particle content Opus Bulk Fill APS decreases the translucency of the material. This could increase light scattering and decrease light transmittance. However, 3M ESPE claims that this resin composite works with its own patented system, called (smart contrast ratio management). This system controls the interaction and refractive index between the resin composite component and filler particles, thereby increasing the opacity of the material during photoactivation.[38,43] This implies that the material is more translucent before photoactivation, thus allowing light to pass into deeper regions to achieve an adequate polymerization depth. In addition, during photoactivation, the contrast ratio of the material changes and it becomes more opaque, which is beneficial as long as the light reaches the material properly. This could explain the higher bond strength values achieved with the monowave light source (Elipar DeepCure-L) compared to the polywave light source (Valo) because Elipar DeepCure-L has a higher light intensity (1470 mW/cm²). Moreover, this device has a wavelength of only one profile, and knowing that Filtek One Bulk Fill contains camphorquinone as the only photoinitiator, it would allow the total absorption of the light, favouring the bond strength. The presence of zirconia/silica also improved the mechanical properties of Filtek One Bulk Fill, which is supported by the results obtained by Kiliç et al.[44]

The Tetric N-Ceram Bulk Fill resin composite was light-cured with a polywave unit at high power (1400 mW/cm^2 × 12s) presented higher bond strength values because it had a germanium-based photoinitiator (ivocerin) with a higher curing activity than camphorquinone. Ivocerin initiates its polymerization activity by producing two free radicals, making it more efficient than the camphorquinone system in which only one free radical is produced. In addition, the refractive index of the resin composite monomers matches that of the filler particles, leading to a translucent structure that facilitates light penetration with an adequate depth of cure.[5,20,34] Therefore, the presence of ivocerin causes a short light application time with high power (1400 mW/cm^2 × 12s), producing sufficient radicals. Additionally, the Tetric N-Ceram Bulk Fill, which counteracts the shrinkage phenomenon, contains urethane dimethacrylate (UDMA) which is responsible for specific chain transfer reactions and provides an alternative pathway for further polymerization.[1,6,23] This reaction generates faster movement of radicals in the chain structure, resulting in enhanced polymerization and monomer conversion by achieving high reactivity and conversion rates with lower shrinkage.[1,34,45] In addition, Tetric N-Ceram Bulk Fill contains prepolymerized particles that also play a role in reducing polymerization stress, which would improve some of its mechanical properties.[21] Despite the above, the Tetric N-Ceram Bulk Fill exhibited lower bond strength at standard power (1000 mW/cm^2 × 20s), which contradicts the results of Besegato et al,[5] who reported that low-power irradiation over a long time interval provides slower polymerization, thus improving the mechanical properties of resin composites by forming longer chains with higher molecular weights than those formed with high-power irradiation.

Failure type analysis indicated a higher percentage of mixed failures in the Opus Bulk Fill and Tetric N-Ceram Bulk Fill, regardless of the curing unit, whereas the Filtek One Bulk Fill showed adhesive failures in the polywave unit. Mixed and adhesive failures correspond to the most common types of failure in µTBS studies of bulk-fill resins.[6,15] Adhesive failures occurred in the Filtek One Bulk Fill and were associated with lower adhesive strength values obtained at standard and high powers. However, these values did not differ significantly with additional power. Therefore, the curing mode has no impact on the type of failure, but it affects the bond strength, which in turn is related to the resin composition.[20] It should be noted that some authors[46,47] reported that the adhesive failure type could also be associated with an adequate distribution of forces at the adhesive interface during the strength test. Mixed failures are related to the partial degradation of the resin-dentin interface with aging due to thermal cycling.[48] This, in turn, reflects the better adhesive adaptation and better penetration of the resin composite into the dentin surface.[42]

In the present study, 10,000 thermal cycles were performed to simulate intraoral temperature changes during eating and drinking, corresponding to approximately one year of in vivo functioning.[6] It is also relevant to mention that the collection of teeth was obtained from a specific age group (20–30 years) because dentin development changes with time.[25] If the teeth are very different in age, histophysiological changes in dentin could bias the bond strength results.

A limitation of the present study is that the in vitro evaluation of restorative materials does not simulate the dynamic pH changes caused by diet and saliva, which are factors that also lead to the degradation of resin composites, nor do they replicate the forces produced in the oral environment, such as compression due to masticatory loads. Therefore, it is recommended that the results obtained be interpreted with caution because, as an in vitro study, they cannot be extrapolated to the clinical field. Further studies are required to explain the shrinkage stress phenomenon during polymerization under the influence of high irradiation and short exposure. Properties such as surface roughness and microhardness should also be evaluated as they can be affected. Finally, it is recommended to evaluate the temperature variation because it has been reported that the temperature change is proportional to the increase in intensity, which could generate adverse effects on the pulp and some degree of shrinkage in the resin composite.[27,49] Additionally, clinicians should keep in mind that a reduced curing time should be used with caution, considering the composition of each material and the LCU used, as each manufacturer has different formulations and this could affect the success of the restoration. Furthermore, this option could be considered in patients who do not tolerate long operating times, such as children and older adults.

This study shows that the bond strength of the tested bulk-fill resin composites depends on the light-curing protocol[5,21,35,39] and their composition.[2,5,8,24,25] Although some authors suggest the use of higher irradiance emitted in a shorter time to optimise the time during restorative procedures.[22–25] The results of the present study are clinically important because they suggest that the use of a reduced curing time should be performed with caution, taking into account the composition and characteristics of each resin composite. It is essential that clinicians have knowledge of LCUs and which of them adequately activates each type of resin composite.

Conclusion

The presence of alternative photoinitiator systems that are more reactive than camphorquinone produced higher microtensile bond strength in Tetric N-Ceram Bulk Fill and Opus Bulk Fill resins when light-cured with a high and standard polywave unit, respectively, compared to Filtek One Bulk Fill resins. Finally, Tetric N-Ceram Bulk Fill and Opus Bulk Fill resins had the highest percentage of mixed failures, while Filtek One Bulk Fill resin had adhesive failures, which was related to its lower microtensile bond strength.

Data Sharing Statement

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Ethic Approval and Consent to Participate

This study adhered to the bioethical principles of medical research with human beings in the Declaration of Helsinki. This study was approved by the Ethics and Research Committee of the Faculty of Stomatology of the Universidad Privada Antenor Orrego (official letter no. 0360-2022-D-EPG-UPAO). The teeth used were voluntarily donated and extracted for orthodontic or prosthetic reasons with prior informed consent.

Acknowledgments

We thank the team of the "Materiales Dentales" Research Line of the School of Stomatology of the Universidad Privada San Juan Bautista, Peru, for their constant support in the preparation of this manuscript.

Author Contributions

All authors made a significant contribution to the work reported, whether in the conception, study design, execution, acquisition of data, analysis, and interpretation, or in all these areas, took part in drafting, revising, or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

This research received no external funding.

Disclosure

The authors declare that they have no conflicts of interest regarding the development and publication of this study.

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