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Influence of Different Curing Modes on Polymerization Behavior and Mechanical Properties of Dual-Cured Provisional Resins

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Clinical Relevance

For dual-cured provisional resins, the light-curing mode may contribute to the enhancement of their mechanical properties and reduction of chair time.

SUMMARY

This study determined the influence of curing mode on polymerization behavior and mechanical properties of dual-cured provisional resins. Three dual-cured bisacryl-based provisional resins were used: Tempsmart (TS; GC Corp), Luxatemp Automix Solar (LX; DMG Chemisch Pharmazeutishe Fabrik GmbH), and Integrity Multi·Cure (IG; Dentsply Caulk). A self-cured bisacryl-based provisional resin, Protemp Plus (PP; 3M ESPE) and a conventional poly(methyl methacrylate) (PMMA) provisional resin, Unifast III (UF; GC Corp) were used as controls. The inorganic filler content and coefficients of linear thermal expansion of the test materials were measured. Six specimens of each material were used to determine the flexural strength, elastic modulus, and resilience. The changes in ultrasound velocity during polymerization were measured. The average inorganic filler contents of the provisional resins, apart from UF, ranged from 24.4 to 39.3 wt%. The highest inorganic filler content was determined for LX, whereas TS showed the lowest value among the tested materials. The average coefficients of thermal expansion of the tested provisional resins ranged from 77.3 to 107.7 ($\times 10^{-6}$/°C). TS and IG showed significantly

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lower thermal expansions than the other tested provisional resins. The mean flexural strengths of the provisional resins ranged from 70.4 to 122.6 MPa, the mean elastic moduli ranged from 1.8 to 3.7 GPa, and the mean resilience of the provisional resins ranged from 1.1 to 2.3 MJ/mm^3, respectively. Dual-cured provisional resins showed significantly higher flexural strengths than the PMMA resin. However, in all cases, the light-curing mode showed significantly higher flexural strengths than the self-curing mode. In the initial polymerization phase, dual-cured resins in the light-curing mode showed a rapid increase in the speed of sound (*V*) during light irradiation, followed by a slower increase. Conversely, the dual-cured resins in the self-curing mode showed a slower initial increase, followed by a rapid increase. Although no significant difference in *V* was observed between 10 and 15 minutes in the light-curing mode of all tested dual-cured resins, a significantly higher *V* value was obtained at 15 minutes than at 10 minutes in the self-curing modes for LX and IG. Regardless of the curing mode, tested dual-cured provisional resins showed superior mechanical properties than the conventional PMMA provisional resin. However, dual-cured provisional resin flexural properties and polymerization behavior were affected by the curing mode. This study indicated that the light-curing mode might be recommended for all dual-cured provisional resins because of the enhancement of their mechanical properties and reduction of chair time.

INTRODUCTION

Provisional restorations are fabricated to maintain tooth position, seal prepared teeth, protect margins, and establish appropriate vertical dimension during the interim period between preparing a tooth and seating a final restoration. In addition to their immediate protective, functional, and stabilizing value, interim restorations are useful for determining the functional occlusion and esthetic parameters, thereby enabling an optimum treatment outcome to be identified before definitive procedures have been completed.[1-4] Although digital dentistry, including computer aided design and manufacturing technology, has been developed, provisional restorations can be essential for responding to patient demands for detail and achieving a realistic trial that is similar to the final restorations. In some cases, provisional restorations are required to function for extended intervals and provide long-term stability while the adjunctive treatment is completed. In particular, for complex treatments, including dental implant therapy, maintaining the long-term durability of provisional restorations in the oral environment is required.[5-7]

In the last decade, bis-acryl–based resins containing inorganic fillers have been introduced and used extensively as provisional materials. This type of provisional resin can maintain long-term stability in the oral environment because of enhanced mechanical properties and wear resistance.[8-10] Bis-acryl–based resins have different curing modes, and several new products use a dual-curing mode. However, dual-cured resin-based materials have been reported to exhibit poor mechanical properties when the polymerization reaction is initiated by chemical curing alone.[11-14] Thus, the curing mode might affect the mechanical properties of the dual-cured provisional resins.

When considering the handling properties of provisional resins, the working and setting times are important in clinical situations. To achieve precise fitting to the abutment tooth during the fabrication of provisional restorations, proper flow, wetting, and the plastic properties of materials before complete polymerization are required. Changes in these properties depend on polymerization kinetics. However, quantitatively determining the polymerization kinetics of resin-based materials as a function of time using destructive testing methods such as flexural, compressive, or hardness measurements is difficult. By contrast, the ultrasonic method enables the noninvasive analysis of materials and monitoring of changes in their properties as a function of time. Ultrasonic devices have been used to detect carious lesions and to measure the setting process of resin cements or core buildup resins.[15-17] Because the speed of sound is sensitive to the viscoelastic properties of materials, the polymerization behavior of a material can be quantified by monitoring ultrasonic propagation.[18]

The purpose of this study was to determine the influence of curing mode on the mechanical properties and polymerization behavior of dual-cured bis-acryl provisional resins using an ultrasonic device. In addition, the mechanical properties and polymerization behavior of dual-cured bis-acryl provisional resins were compared with those of a conventional poly(methyl methacrylate) (PMMA) provisional resin and with those of a self-cured bis-acryl provisional

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Table 1: *Materials used in this study*

Code	Provisional resins (shade: lot no.)	Main components	Manufacturer
TS	Tempsmart (A2: 1505171)	Bis-GMA, UDMA, dimethacrylate, silane treated amorphous silica, photo initiator, pigment	GC Corp
LX	Luxatemp Automix Solar (A2: 715884)	Multifunctional methacrylate, glass filler, catalyst, stabilizer, additives	DMG
IG	Integrity Multi Cure (A2: 140808)	Bis-acrylate, multifunctional methacrylate, barium boroaluminosilicate glass filler, catalyst, photoinitiator, stabilizer	Dentsply Caulk
PP	Protemp Plus (A2: Base 498865) (A2: Catalyst 495535)	Dimethacrylate (BISEMA 6), silane treated silica, silane treated amorphous silica, ethanol, 2, 2′-[(1-methylethylidene)-bis(4,1-phenyleneoxy)] bisethyl diacetate, benzyl-phenyl-barbituric acid	3M ESPE
UF	Unifast III (A2: Powder 1103231) (Liquid 1507291)	Powder: ethyl-methyl methacrylate polymer, polymethylmethacrylate, barbituric acid derivative, organic copper compound, pigments Liquid: methyl methacrylate, *N*,*N*-dimethyl-*p*-toluidine trimethylolpropane, ethylene glycol dimethacrylate	GC Corp

Abbreviations: Bis-GMA, bisphenol A glycidyl dimethacrylate; UDMA, urethane dimethacrylate.

resin. The null hypotheses to be tested were the following: 1) dual-cured bis-acryl provisional resins would not differ depending on curing mode with respect to mechanical properties and polymerization behavior, and 2) dual-cured bis-acryl provisional resins would not differ in their features from a PMMA provisional resin or a self-cured bis-acryl provisional resin.

METHODS AND MATERIALS

Materials

Three dual-cured bis-acryl provisional resins were used: 1) Tempsmart (TS; GC Corp, Tokyo, Japan), 2) Luxatemp Automix Solar (LX; DMG Chemisch-Pharmazeutishe Fabrik GmbH, Hamburg, Germany), and 3) Integrity Multi Cure (IG; Denstply Caulk, Milford, DE, USA). A self-cured bis-acyl provisional resin Protemp Plus (PP; 3M ESPE, St Paul, MN, USA) and a conventional PMMA provisional resin UniFast III (UF; GC Corp) were used as control materials (Table 1). A visible-light curing unit (Optilux 501, SDS Kerr, Danbury, CT, USA) was used, and the light irradiance (average, 600 mW/cm^2) of the curing unit was checked using a dental radiometer (model 100, SDS Kerr).

Inorganic Filler Content

Inorganic filler contents of the materials were measured using thermogravimetry/differential thermal analysis (TG/DTA6300 thermogravimeter, Seiko Instruments Inc, Tokyo, Japan). For each provisional resin tested, a mixed paste (50 mg) was heated in the thermogravimeter from 25°C to 800°C at a heating rate of 10°C/min until the organic components were completely incinerated. The weight of the residual resin paste was automatically measured by the built-in highly sensitive and accurate horizontal differential balance, and the inorganic filler content (wt%) was calculated using the compensating blank curve. Three measurements were conducted to obtain an average inorganic filler content (wt%). According to the manufacturer's material safety data sheet, the PMMA resin UF does not contain inorganic filler; therefore, the inorganic filler content measurement for UF was omitted.

Coefficient of Linear Thermal Expansion

The coefficients of linear thermal expansion of the test materials were measured using a thermomechanical analyzer (TMA/SS6300, Seiko Instruments Inc). For each provisional resin tested, a mixed provisional paste was condensed into a cylindrical Teflon (Sanplatec Corp, Osaka, Japan) mold 8.0 mm high and 3.0 mm in diameter. For dual-cured resins in the light-curing mode, light irradiation was carried out from the top and bottom sides of the mold for 40 seconds each, and the mold was then cut with a sharp scalpel and removed from the cured provisional resin. To ensure polymerization, the center of the specimen was irradiated perpendicular to the axis for 40 seconds, and the irradiation was then repeated for the opposite side. These tests were not performed for dual-cured resins in the self-curing mode. Because heat curing during the course of thermal expansion testing may induce the polymerization of the unreacted monomer, an equivalent

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degree of conversion may be achieved regardless of curing modes. Therefore, the tests were performed only in the light-curing mode. Before the measurements were conducted, specimens were stored under dark conditions at 25 ± 1°C for 24 hours. Three specimens per provisional resin were prepared and separately tested in a thermomechanical analyzer at a heating rate of 2°C/min from 25°C to 100°C. Thermal expansion measurements were conducted four times per specimen; however, the first measurement outcome was discarded as unreliable. The average coefficient of linear thermal expansion ($\times 10^{-6}$/°C) was measured over a temperature range of 50°C, which is the same as that used in standard thermal cycling experiments, starting at a low temperature of 30°C to avoid any influence of fluctuation in ambient temperature.

Flexural Properties

The flexural properties of provisional resins were tested according to ISO #4049 specifications. Following the manufacturer's instructions, we mixed and compacted each provisional resin into a stainless-steel split mold of dimensions $25 \times 2 \times 2$ mm; the mold was positioned on a glass slide. After the hardened specimen was removed from the mold, all six sides were wet polished with #1200 silicon carbide papers (Fuji Star type DDC, Sankyo Rikagaku Co, Ltd, Saitama, Japan). Dual-cured provisional resins were evaluated with or without light irradiation. For the light-curing mode, resin paste was condensed into the mold, the middle third of the specimen was first irradiated for 30 seconds, and the remaining thirds were irradiated for 30 seconds each. All specimens were stored under dark conditions for 24 hours in distilled water at 37 ± 1°C before measurements. After the storage time, six specimens per test group were subjected to the three-point bending flexural strength test (span length, 20.0 mm) using a universal testing machine (model 5500R, Instron Corp, Canton, MA, USA) at a cross-head speed of 1.0 mm/min until breaking of the specimen. The flexural strength (F) and the modulus of elasticity (E) were determined from the stress–strain curve using computer software (Bluehill v. 2.5, Instron Corp, Canton, MA, USA) linked to the testing instrument. The modulus of resilience (R) was calculated using the following equation: $R = F^2/2E$.[19]

Ultrasonic Measurement

The ultrasonic measurement system used in this study was comprised of a pulser-receiver (5900PR, Panametrics, Waltham, MA, USA), two different types of transducers (M203 and V112, Panametrics), and an oscilloscope (WaveRunner LT584, LeCroy, Tokyo, Japan). One of the transducers (V112) was built into the sample stage. A transparent cylindrical mold (2.0 mm in height and 4.0 mm in diameter) was placed on the stage on top of the built-in transducer (M203). Following the manufacturer's instructions, we mixed the provisional resins and condensed them into the transparent mold at a temperature of 23 ± 1°C and relative humidity of 50 ± 5%. For dual-cured provisional resins in the light-curing mode, light guide-tips were placed on horizontally opposite sides of the mold, sandwiching the sample. The sample was irradiated for 30 seconds simultaneously from both sides, beginning 30 seconds after mixing. In the self-curing mode, this step was omitted.

Ultrasound measurements were begun 30 seconds after mixing for both polymerization modes. The transducers were connected to the pulser-receiver in through-transmission mode, and 16-μJ pulses were applied at a pulse repetition frequency of 500 Hz. The signal was captured using an oscilloscope. No heat generation was observed from the transducers during measurement, and the system was calibrated following standard procedures before each specimen was measured. The pulses were applied continuously from 30 seconds after mixing. Transmission times were recorded every 10 seconds until 5 minutes after mixing and then every 30 seconds until 15 minutes after mixing. The propagation speed of ultrasound (V) was calculated from sample thickness and transmission time. The three dual-cured provisional resins were tested in both the self-curing and light-curing modes, and PP and UF were tested only in the self-curing mode. Five samples were tested in each condition for all of the materials tested.

Scanning Electron Microscopy Observations

The surfaces of the polymerized materials were polished to a high gloss with abrasive discs (Fuji Star type DDC, Sankyo Rikagaku Co, Ltd) followed by a series of diamond pastes to 0.25-μm particle size (DP-Paste, Struers, Ballerup, Denmark). The polished surfaces were then subjected to argon ion beam etching (IIS-200ER, Elionix, Tokyo, Japan) for 40 seconds, with the ion beam directed at the polished surface (accelerating voltage, 1.0 kV; ion current density, 0.4 mA/cm^2). The surfaces were then coated with a thin film of gold in a vacuum coating evaporator (Quick Coater, model SC-701, Sanyu Denchi Inc, Tokyo, Japan). Observations were carried out using a scanning electron microscope

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Table 2: *Inorganic filler contents of provisional resins*[a]

Code	Inorganic filler content (wt%)	Tukey group	Coefficient of linear thermal expansion ($\times 10^{-6}$/°C)	Tukey group
TS	24.4 (0.5)	d	77.3 (1.7)	a
LX	39.3 (0.3)	a	99.4 (2.5)	b
IG	37.5 (0.8)	b	80.7 (2.4)	a
PP	30.8 (0.6)	c	105.8 (1.6)	c
UF	—	—	107.7 (0.8)	c

[a] *Standard deviation is noted in parentheses. Same lowercase letters in vertical columns indicate no difference at the 5% significance level.*

(SEM; FE-8000, Elionix) operated at an accelerating voltage of 10 kV.

Statistical Analysis

A one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test (α=0.05) was used for analysis of inorganic filler content, coefficient of thermal linear expansion, flexural strength, elastic modulus, and resilience of the provisional resin. Ultrasound velocity measurements for all resins and conditions were compared using one-way ANOVA followed by Tukey's HSD test (α=0.05). This comparison was performed for measurements taken at the same time point for each of four times. The statistical analyses were performed using a software system (Sigma Plot ver. 11.0, SPSS Inc, Chicago, IL, USA).

RESULTS

Inorganic Filler Content and Coefficients of Thermal Expansion

The average inorganic filler contents and coefficients of thermal expansion are listed in Table 2. The average inorganic filler contents of the provisional resins, apart from UF, ranged from 24.4 to 39.3 wt%. The highest inorganic filler content was determined for LX, whereas TS showed the lowest value among the tested materials, and all differences were statistically significant. The average coefficients of thermal expansion of the tested provisional resins ranged from 77.3 to 107.7 ($\times 10^{-6}$/°C). TS and IG showed significantly lower values than the other tested provisional resins. The difference between LX, PP, and UF was statistically significant.

Flexural Properties

The results of flexural properties testing are shown in Table 3. The mean flexural strengths of the provisional resins ranged from 70.4 to 122.6 MPa, and the mean elastic moduli ranged from 1.8 to 3.7 GPa. Regardless of curing mode, dual-cured provisional resins showed significantly higher flexural strengths than the conventional PMMA resin (UF). However, for all of the dual-cured resins tested, significantly higher flexural strengths were observed for the light-curing mode than for the self-curing mode. The bis-acryl resins, apart from LX, showed higher elastic moduli than UF. In addition, for dual-cured resins, the light-curing mode showed higher elastic moduli than the self-curing mode, except for TS. The average resilience of the provisional resins ranged from 1.1 to 2.3 MJ/mm^3. All dual-cured tested resins, regardless of curing mode, showed signifi-

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Table 3: *Flexural strength, elastic modulus, and resilience of provisional resins*[a]

Code	Flexural strength (MPa)	Tukey group	Elastic modulus (GPa)	Tukey group	Resilience (MJ/mm^3)	Tukey group
Light-curing						
TS	118.1 (4.3)	a,b	3.7 (0.3)	a	1.9 (0.2)	b,c
LX	92.2 (2.8)	e	2.4 (0.2)	c	1.8 (0.2)	c
IG	122.6 (5.1)	a	3.4 (0.3)	a	2.2 (0.3)	a,b
Self-curing						
TS	106.7 (2.6)	c,d	3.4 (0.4)	a	1.8 (0.2)	c
LX	82.3 (3.7)	f	1.8 (0.1)	d	1.9 (0.1)	b,c
IG	113.5 (2.5)	b	2.9 (0.1)	b	2.3 (0.1)	a
PP	109.5 (2.9)	b,c	3.3 (0.3)	a,b	1.8 (0.1)	c
UF	70.4 (1.3)	g	2.2 (0.1)	c,d	1.1 (0.1)	d

[a] *Standard deviation is noted in parentheses. Same lowercase letters in vertical columns indicate no difference at the 5% significance level.*

Fig 1

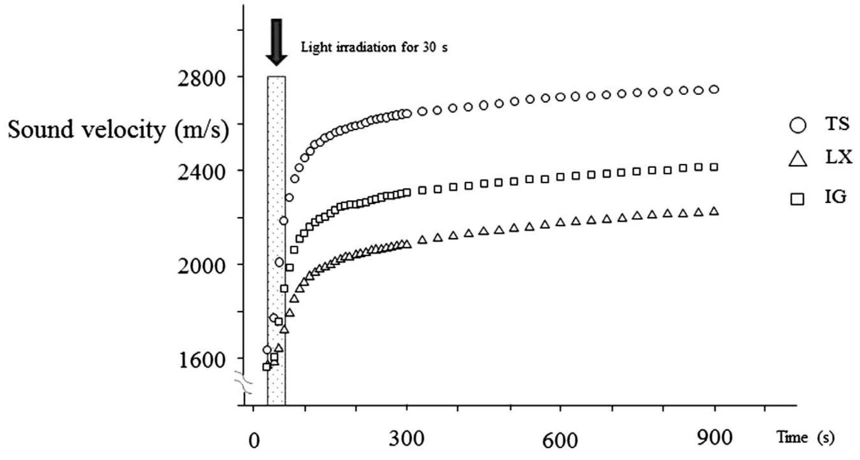

Figure 1. *Changes in* V *values in light-curing mode as a function of time from 30 to 900 seconds after mixing.*

cantly higher resilience than UF. In addition, no significant difference was observed between the light-curing and self-curing modes.

Ultrasonic Measurement

The results for ultrasonic velocity (*V*) in provisional resins are shown in Figures 1 and 2 and in Table 4. Changes in *V* values as a function of time depend on the type of provisional resin and curing mode. In the light-curing mode, a rapid increase in *V* values during light irradiation followed by a slower increase was observed (Figure 1). Although there was no significant difference in the *V* values of TS between five and 10 minutes, LX and IG showed significantly higher *V* values at 10 min than at five minutes. TS showed significantly higher *V* values than the other dual-cured resins at each time point.

In the self-curing mode, a much slower increase in *V* values, followed by a rapid increase was observed. However, TS, IG, and PP (Figure 2) had short initial segments (approximately 30 seconds) that exhibited little change, followed by a sharp increase. By contrast, LX and UF had a long flat segment that lasted for approximately 180 seconds before *V* substantially began to increase. LX and IG showed significantly higher *V* values at 15 minutes than at 10 minutes, whereas TS, PP, and UF exhibited no significant differences between 10 and 15 minutes. Although TS showed significantly higher *V* values than the other dual-cured resins in the self-curing

Fig 2

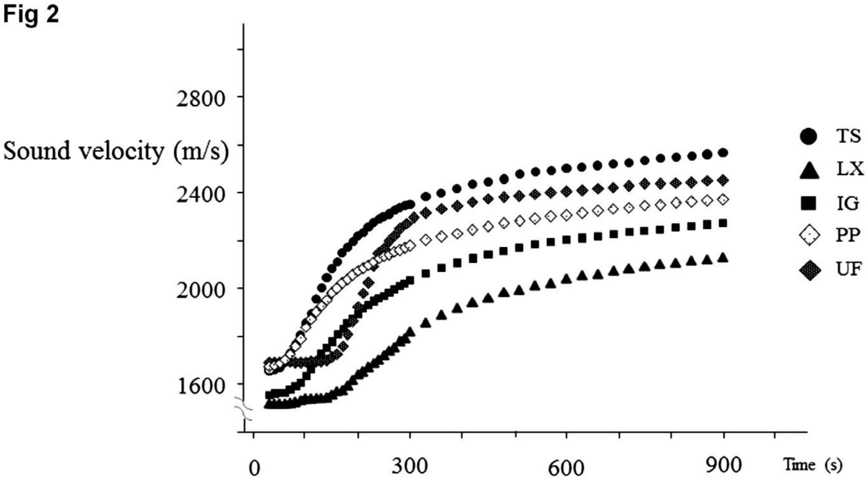

Figure 2. *Changes in* V *values in self-curing mode as a function of time from 30 to 900 seconds after mixing.*

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Table 4: *Changes in* V *values in provisional resins as a function of time from 30 seconds to 15 minutes*[a]

Code	30 seconds	One minute	Five minutes	10 minutes	15 minutes
Light-curing					
TS	1661.8 (13.5)^{aA}	2186.9 (39.0)^{bA}	2645.6 (56.0)^{cA}	2714.6 (65.6)^{cdA}	2746.2 (71.2)^{dA}
LX	1570.9 (20.8)^{aB}	1720.4 (57.3)^{bC}	2091.0 (48.9)^{cD}	2176.4 (47.5)^{dD}	2223.8 (50.1)^{dDE}
IG	1559.3 (26.8)^{aB}	1899.8 (22.0)^{bB}	2305.9 (39.7)^{cB}	2371.9 (44.1)^{dC}	2417.1 (51.4)^{dC}
Self-curing					
TS	1656.8 (16.7)^{aA}	1695.7 (37.5)^{aC}	2353.5 (67.3)^{bB}	2501.5 (72.7)^{bcB}	2567.8 (72.5)^{cB}
LX	1538.0 (26.9)^{aB}	1542.5 (28.7)^{aD}	1827.1 (44.5)^{bE}	2046.0 (56.2)^{cE}	2136.8 (58.0)^{dE}
IG	1556.3 (6.5)^{aB}	1566.0 (10.4)^{aD}	2035.8 (41.1)^{bD}	2202.4 (31.3)^{cD}	2274.5 (31.6)^{dD}
PP	1674.1 (36.5)^{aA}	1702.4 (35.6)^{aC}	2180.1 (69.6)^{bC}	2307.0 (82.6)^{cC}	2372.2 (87.2)^{cCD}
UF	1691.8 (91.6)^{aA}	1693.2 (92.7)^{aC}	2294.0 (94.2)^{bBC}	2407.8 (69.3)^{bcBC}	2454.1 (92.1)^{cdBC}

[a] *Standard deviation is noted in parentheses. Same lowercase letters in horizontal rows indicate no difference at the 5% significance level. Same capital letters in vertical columns indicate no difference at the 5% significance level.*

mode at each measuring point, in the case of the light-curing mode, no significant difference was detected with UF at any time point.

SEM Observations

SEM micrographs of the five tested materials after argon-ion etching are presented in Figures 3 through 7. Clear differences in filler size, shape, and distribution were observed. Nano-sized filler particles were observed for TS, and these fillers were more densely packed than those observed for LX and IG (Figures 3 through 5). In the case of LX, 0.02- to 2.5-μm irregular glass filler particles were observed (Figure 4b). In the case of IG, although filler shape and distribution were similar to those of LX, the typical filler size was much smaller than that of LX, approximately 0.02 to 1 μm (Figure 5b). For PP, 0.05- to 0.2-μm spherical filler particles were observed (Fig. 6b). The conventional PMMA resin UF contains 20- to 50-μm spherical polymer particles (Fig. 7b).

DISCUSSION

Marginal adaptation of provisional restoration is important for maintaining a healthy condition of periodontal tissue and for protecting dental pulp from bacterial invasion. One of the desirable mechanical properties of provisional materials is their expansion rate, which is similar to that of tooth substrate. Changes in temperature might induce dimensional changes in the substrates, which could lead to channels forming in the materials.[20] Relatively large differences in the thermal expansion rate between the tooth and provisional restoration may induce gaps in the vicinity of the finishing margin, resulting in penetration of oral fluids and degradation of the temporary cement.

In this study, the average coefficients of thermal expansion of the tested materials ranged from 77.3 to 107.7 ($\times 10^{-6}/^{\circ}C$), which is approximately seven to 10 times higher than tooth thermal expansion and noticeably higher than the coefficients of thermal expansion of resin composites.[20] A higher inorganic filler content in resin-based materials is expected to reduce thermal expansion because of the low thermal expansion coefficients of the inorganic fillers commonly used in this application. However, despite of its higher inorganic filler content, LX exhibited a significantly higher thermal expansion than the dual-cured resins TS and IG. Furthermore, we found no correlation between inorganic filler content and the thermal expansion. Furuichi and others[21] reported that no correlation exists between the inorganic filler content and coefficient of thermal expansion of resin cements and concluded that the coefficients of thermal expansion were material dependent. Therefore, in bis-acryl resins, other factors such as the type of matrix resin and/or size of filler particles might significantly affect the thermal properties, as in the case of resin cements. Some bis-acryl resins include a plasticizer that reduces the glass-transition temperature (Tg) of polymers by weakening the links between the polymer chains and increasing their mobility.[22] However, TS does not contain a plasticizer, which may explain why it exhibited lower thermal expansion despite its lower inorganic filler content.

Fracture-related material properties such as fracture resistance, elasticity, and the marginal degradation of materials under stress have typically been evaluated through the determination of material parameters, such as compressive, tensile, and flexural strengths and fracture toughness.[23,24] From the results of the flexural tests, dual-cured resins

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Fig 3

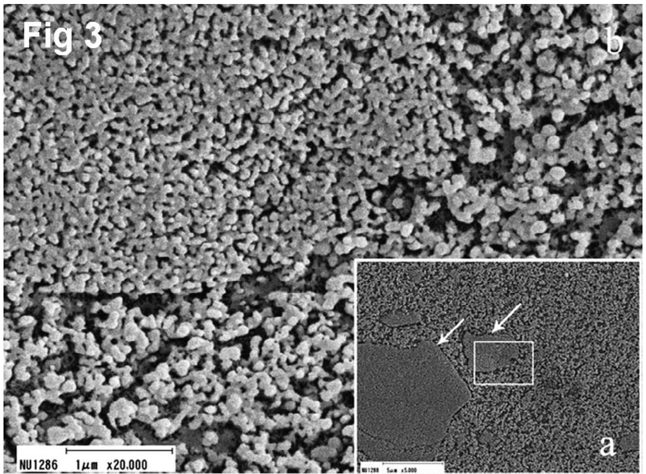

Fig 4

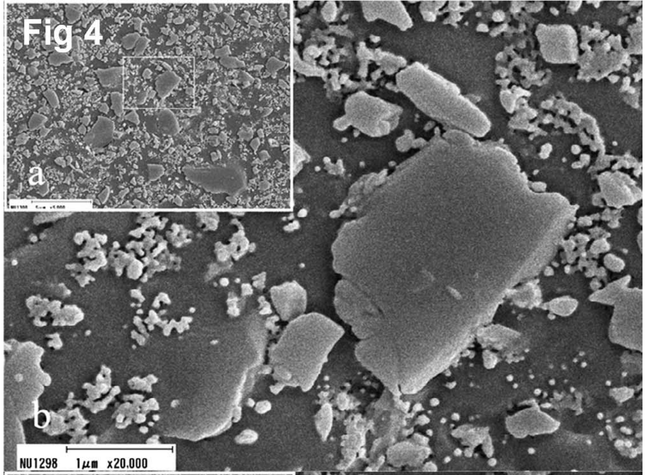

Fig 5

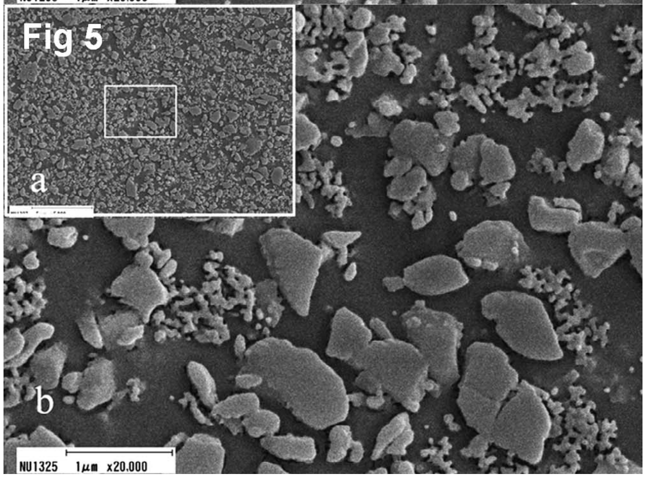

Figure 3. *SEM micrographs of the argon ion-etched surface of TS resin at magnifications of (a) 5000× and (b) 200,000×.*

Figure 4. *SEM micrographs of the argon ion-etched surface of LX resin at magnifications of (a) 5000× and (b) 200,000×.*

Figure 5. *SEM micrographs of the argon ion-etched surface of IG resin at magnifications of (a) 5000× and (b) 200,000×.*

Fig 6

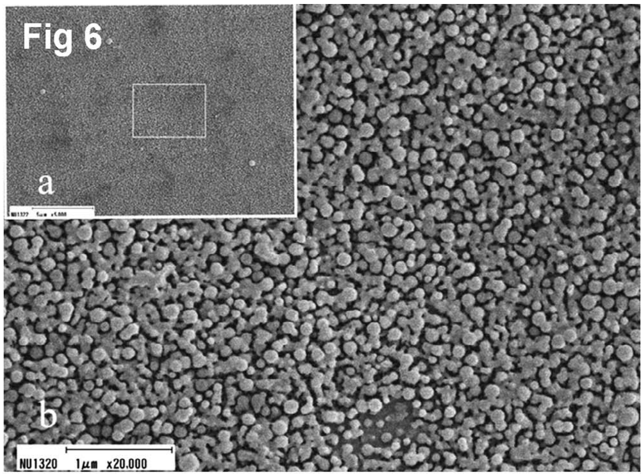

Fig 7

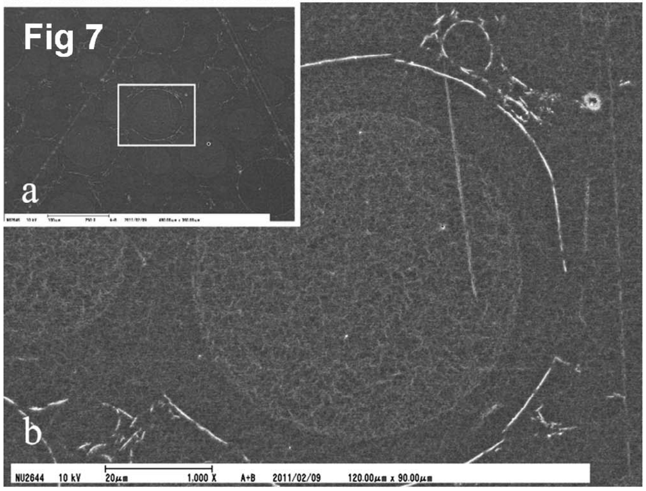

Figure 6. *SEM micrographs of the argon ion-etched surface of PP resin at magnifications of (a) 5000× and (b) 200,000×.*

Figure 7. *SEM micrographs of the argon ion-etched surface of UF resin at magnifications of (a) 100× and (b) 1000×.*

showed significantly higher flexural strength and resilience than the conventional PMMA resin, regardless of curing mode. Although the mechanical properties of UF were inferior to those of dual-cured resins regardless of curing mode, the flexural properties of PP were similar to those of dual-cured resins. Therefore, with respect to the mechanical properties, the null hypothesis that dual-cured bis-acryl resins would not differ from a conventional PMMA resin or a self-cured bis-acryl provisional resin was partially rejected. Bis-acryl resins contain multifunctional monomers that increase strength via cross-linking with other monomers[25] and also include inorganic fillers that can distribute the load stress and inhibit crack propagation.[8] In particular, the presence of filler particles increases the fracture energy and creates a pinning effect in crack propagation.[26] On the other hand, conventional

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PMMA resin is composed of monofunctional, low-molecular-weight, linear molecules that demonstrate lower strength and rigidity.[27,28] Moreover, the bis-acryl resins used in this study were in cartridge-based dispensing systems, which might contribute to a more accurately proportioned and consistent mix. By contrast, the PMMA resin was hand mixed, and air entrapment may have occurred and resulted in lower strength values.[10]

Among the dual-cured resins tested, LX exhibited significantly lower flexural strength than the others, regardless of curing mode. SEM observations of the polished surfaces revealed that LX had a wider filler particle size distribution and larger interparticle spacing than the other dual-cured resins. We speculated that the larger interparticle spacing interferes with the pinning effect in crack propagation due to filler particles. In this study, bis-acryl resins, apart from LX, showed significantly higher flexural moduli than the UF resin. In general, resin-based materials exhibit an increase in elastic modulus with increasing inorganic filler load.[29,30] However, to maintain flexibility and plasticity after polymerization, some bis-acryl resins contain a plasticizer. The plasticizer is believed to not be chemically bonded to the plastic network.[22] Although it has relatively low filler load, TS lacks a plasticizer, which is speculated to have contributed to its relatively high elastic modulus.

The results of ultrasonic measurements indicate that the change of V as a function of time depends on the type and curing mode of provisional resins. A comparison of light-curing and self-curing modes of dual-cured resins reveals that the curves of V values are clearly different (Figures 1 and 2). When light irradiation was conducted for 30 seconds, a rapid increase in the V value was observed. Although significant differences were observed in the V values between 30 seconds and 1 minute after mixing in light-curing mode, there was no significant difference between 30 seconds and 1 minute in the self-curing mode. When the 15-minute V value was defined as 100% for each tested material, V values from 77% to 80% were observed at 1 minute in the light-curing mode of dual-cured resins. However, in the self-curing mode of dual-cured resins, V values at 1 minute ranged from 66% to 69%. Therefore, the null hypothesis that dual-cured provisional resins would not differ depending on curing mode with respect to mechanical properties and polymerization behavior was rejected.

Although the V values of dual-cured resins in the light-curing mode were material dependent, the rising curves exhibited similar shapes. Photoinitiated polymerization has been speculated to occur quickly after an induction period associated with the consumption of polymerization inhibitor and dissolved oxygen by initiator-derived radicals.[31] By contrast, in the case of the self-curing mode, the line graphs showed different trends among the tested resins. In particular, TS, IG, and PP have short initial segments with little change, followed by a sharp rise; by contrast, LX and UF have a long flat segment before V begins to rise significantly. This shows that LX has a longer working time than the other dual-cured provisional resins. It can be inferred that changes in V values might be attributable to differences in composition, including the composition of the catalyst system. In addition, this result indicates that the working time and setting time of provisional resins in self-curing mode are much more material dependent than in light-curing mode. During the polymerization process, the material properties of the resins change from a viscous liquid state to a glassy solid state. Although ultrasonic velocity cannot directly measure the degree of conversion or the strength of the material, it can monitor the viscoelastic properties of the resins in bulk.[32] In addition, ultrasonic measurements enable visualization and quantification of polymerization behavior over time. This information helps researchers not only to grasp the characteristics of polymerization kinetics but also to predict mechanical properties as a function of time.

The main clinical implication of this study is that dual-cured provisional resins have acceptable properties for clinical use in either mode. The results obtained in this study indicated that the light-curing mode might be recommended for all dual-cured provisional resins because of the enhancement of their mechanical properties and reduction of chair time. In addition, to avoid the negative effects of contact with oral fluid in the initial stage of polymerization, the light-curing mode should be used to induce the polymerization reaction for dual-cured provisional resins when provisional restorations are fabricated in situ.

CONCLUSION

Within the limitations of this *in vitro* study, dual-cured provisional resins exhibited mechanical properties superior to those of the conventional provisional PMMA resin UF, they also showed flexural properties similar to those of the self-cured bis-acryl–based provisional resin PP. A comparison of the light-curing and self-curing modes of dual-cured

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resins revealed that the light-curing mode tended to result in higher flexural properties than the self-curing mode. On the basis of the results of ultrasonic measurements, the V value varies as different functions of time, depending on the type of provisional resin and curing mode.

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Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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