Mechanical evaluation of dental trauma splints fabricated using recently-developed photo-polymerizable composites

Wonjoon MOON1*, Hong-Keun HYUN2* and Shin Hye CHUNG1

1 Department of Dental Biomaterials Science, Dental Research Institute, School of Dentistry, Seoul National University, 101 Daehak-ro, Jongno-gu, Seoul 03080, Republic of Korea
2 Department of Pediatric Dentistry, Dental Research Institute, School of Dentistry, Seoul National University, 101 Daehakno, Jongno-gu, Seoul 03080, Republic of Korea
Corresponding author, Shin Hye CHUNG; E-mail: den533@snu.ac.kr

This study aimed to determine functionality and mechanical properties of dental splints. Five splints were tested: a control splint Filtek Z350XT (ZF), two splints with G-Fix (GF) and Light Fix (LF), and two wire-composite splints with ZF (ZW) and Ortho Connect Flow (CW). Periotest values, elastic modulus, flexural, compressive, and diametral tensile strength were measured. ZW and CW showed no significant differences in flexibility in labial or occlusal pressure of upper central incisors. LF, GF, and ZF did not differ in labial or palatal pressure. ZW and CW had higher flexibility than LF, GF, and ZF. LF had the lowest flexural and compressive strength, but the highest diametral tensile strength. This study showed that ZW and CW might be options for flexible splints, whereas LF and GF would be options for rigid splints. Additionally, CW and LF/GF might be simpler alternatives to ZW and ZF, respectively.

Keywords: Trauma, Avulsion, Splint, Resin composite

INTRODUCTION

Splinting traumatized teeth is a critical procedure in the management of luxated, avulsed, and root-fractured teeth1,2. The purpose of dental splinting is to stabilize the injured tooth as long as necessary to ensure that there is no further damage and to protect attachment apparatus to allow the periodontal ligament to regenerate3. Functional flexible splints are recommended because normal functional simulation plays a role in promoting periodontal and pulp healing for the replanted tooth, thus minimizing the risk of development of ankyloses4,5. Flexible splints allow more mobility than in a non-injured tooth based on tooth mobility after fixation and physiological mobility, while semi-rigid splints offer close to normal tooth mobility, and rigid splints offer less than normal tooth mobility6.

Conventional wire-composite splints with stainless steel wires with diameters up to 0.016" or 0.4 mm are widely used and are considered to offer optimal lateral support and vertical flexibility for splinted teeth6,7. The benefits of wire-composite splints are that they can be fabricated using materials available in dental offices, allow the patient to maintain good oral hygiene, and do not cause major damage to the oral soft tissue8. However, application of the splint is time-consuming, since it requires adjustment of the stainless steel wire and application of resin composite after etching, as well as rinsing and bonding the enamel surface on the injured and neighboring teeth. The results may vary depending on the skill of the operator.

The fabrication of splints using resin composite results in rigid splints and is thereby not recommended9,10. Splints using direct prosthetic temporary restorations, such as chemical cured material, Protemp (3M ESPE, St. Paul, MN, USA), and dual cured material, Luxatemp (DMG, Hamburg, Germany), were introduced over ten years ago11. These materials are reported to be aesthetically and hygienically acceptable and to allow semi-rigid splinting12. However, both products are extruded as mixtures using a bulky dispenser, and the setting time may be as long as five minutes, making them inconvenient for clinical use.

Light-curable dental composite, used in conjunction with a light curing unit, allows the on-demand process of polymerization12. Light curing units have been developed to improve the depth of cure and degree of conversion, including quartz-tungsten-halogen, argon-ion lasers, and light-emitting-diodes (LED)12. Most recently, it has been reported that diode-pumped solid-state lasers can provide high power levels and may improve the curing process, eliminating concerns about light attenuation by distance12. In addition, the classic mixture of rigid Bis-GMA and the diluent TEGDMA in the resin matrix has been replaced or supplemented by other molecules with more flexibility in order to improve the degree of conversion13. On the other hand, it was reported that the light intensity affected the degree of conversion but not the flexural strength itself13. Therefore, changes in the chemical composition of the resin matrix might suggest a promising approach to the development of mechanically suitable photo-polymerizable composites for splinting teeth, once a clinically acceptable light source is applied.

Recently, two light-cured flowable resin composite materials, G-Fix (GC, Tokyo, Japan) and Light Fix (Sun Medical, Shiga, Japan), were introduced for temporary splinting. The manufacturer describes G-Fix as a wide
cross-linking monomer and phosphoric ester monomer composition resulting in a highly tough and flexible structure, while Light Fix is described to have an STF ("Strength, Toughness, and Flexibility") monomer with high resiliency and toughness. Both of these products are claimed to be convenient to use because they do not require bonding and can be applied with light polymerization within 20 s after etching, rinsing, and drying.

Another light-cured flowable resin composite adhesive for orthodontic lingual retainers, Ortho Connect Flow (GC), was recently introduced. According to the manufacturer, the primer for this material is integrated into the paste, allowing users to skip the bonding procedure. Using this material as an adhesive resin material for wire-composite splints would be convenient for both the clinician and the patient because of the shorter procedure time without the bonding process. However, to the best of the authors' knowledge, there are no studies comparing the performance or mechanical properties of these new materials in the context of temporary dental splinting.

The purpose of this study was to determine whether splints fabricated using G-Fix, Light Fix, and Ortho Connect Flow meet splint requirements by measuring their flexibilities in comparison with conventional composite and to examine the physical properties of these new resin composites. The first null hypothesis was that splints fabricated using new orthodontic composite adhesives do not differ in performance from conventional wire-composite splints. The second null hypothesis was that splints fabricated using new resin composites do not differ in performance from conventional resin splints. The third null hypothesis was that there are no differences in flexural strength, elastic modulus, compressive strength, and diametral tensile strength of the new resin composites compared to conventional resin composite.

MATERIALS AND METHODS
A dentiform (500A, Nissin Dental, Kyoto, Japan) with acrylic resin teeth was used for this in vitro study. The central incisors (teeth 11 and 21) simulated avulsed teeth with increased vertical and horizontal mobility, whereas the lateral incisors (teeth 12 and 22) and the canines (teeth 13 and 23) simulated uninjured teeth with normal mobility. Premolars (teeth 14 and 24) served as controls. To fabricate the model, the fastening screws in the apical part were removed to allow movement. The premolars were not manipulated. Three models were fabricated for the experiments.

A Periotest device (Periotest Classic, Medizintechnik Gulden, Modautal, Germany) was used to test the simulated mobility. Periotest values have been used to test mobility of traumatized teeth and splinting effects for diverse fixation techniques including composite-wire splints, titanium ring splints, bracket splints, and splints made of composite alone. The Periotest device contains a handpiece with a tapping rod inside. During measurements, the rod was tapped against the labial, palatal, or occlusal surface of the tooth 16 times in 4 s (force 8 g, velocity 0.2 m s\(^{-1}\)). The deflection time was measured, and the computer inside the device converted it to a scaled number between −8 and 50. Negative values represent maximal fixation, as in osseo-integrated implants or ankylosed teeth, whereas high values represent loose objects, such as periodontally affected teeth or dental trauma. According to Periotest values, the central incisors had mobility greater than level III (Periotest 30–50; movement more than 1 mm in any direction) in labial and palatal pressure and between level II (Periotest 20–29; movement of 1 mm in any direction) and III in occlusal pressure. Lateral incisors had mobility between level 0 (Periotest −8–9; no movement) and I (Periotest 10−19; distinguishable sign of movement) in all directions. Premolars had mobility level I, always with negative values.

Five different dental trauma splints were tested, including a splint fabricated using resin composite Filtek Z350XT Flow (ZF; 3M ESPE), two splints fabricated using two resin composites for tooth fixation, G-Fix (GF; GC, Kasugai, Japan) and Light Fix (LF; Sun Medical), and two wire-composite splints fabricated using an orthodontic round stainless-steel wire 0.016\(^\text{"}\) in diameter with either a resin composite Filtek Z350XT Flow (ZW) or an orthodontic composite adhesive Ortho Connect Flow (CW; GC). The materials used for each splint and the fixation methods are described in Tables 1 and 2. To reproduce the application sites, tooth fixation resin composites were applied at contact points on the teeth of 3 mm in length. For the wire-composite splints, the wires were positioned at the 1/2 point of each crown, and the composite was applied in a circular spot 4 mm in diameter. The dental trauma splints fabricated with composites in this study are shown in Fig. 1.

The Periotest device was used to measure the vertical and horizontal mobility of six upper anterior teeth and first premolars, as a control, before and after splinting with five different methods, per the manufacturer’s instructions. Three Periotest readings were taken and averaged for each tooth, and were measured from the labial, palatal, and occlusal directions. To ensure reproducibility of the measurement points, the tapping rod targeted designated spots: 1 mm below the midpoint of the incisor edge for labial measurements, 5 mm below the middle point of the incisor edge for palatal measurements, and the midpoint of the incisor edge for occlusal measurements (Fig. 2). The same measurement process was repeated for all seven models. All readings were taken by the same experienced operator. After the
Table 1  Materials and fixation methods used to fabricate the tested splints

| Code | Materials                                                                 | Splint type                              | Fixation method                                                                 |
|------|---------------------------------------------------------------------------|------------------------------------------|--------------------------------------------------------------------------------|
| ZF   | Filtek Z350 XT Flow (3M ESPE, St. Paul, MN, USA)                          | Composite splint                         | 1. Etch with 35% phosphoric acid (30 s)+wash+air-dry                           |
|      |                                                                           |                                          | 2. Bond+light-cure (10 s)                                                      |
|      |                                                                           |                                          | 3. Apply composite between teeth in the contact region                         |
|      |                                                                           |                                          | 4. Light-cure (10 s)                                                          |
| GF   | G-Fix (GC, Kasugai, Japan)                                                | Commercially available tooth fixation composite splint | 1. Etch with 35% phosphoric acid (30 s)+wash+air-dry                           |
|      |                                                                           |                                          | 2. Apply composite between teeth in the contact region                         |
|      |                                                                           |                                          | 3. Light-cure (10 s)                                                          |
| LF   | Light Fix (Sun Medical, Moriyama, Japan)                                  | Commercially available tooth fixation composite splint | 1. Etch with 35% phosphoric acid (30 s)+wash+air-dry                           |
|      |                                                                           |                                          | 2. Apply composite between teeth in the contact region                         |
|      |                                                                           |                                          | 3. Light-cure (10 s)                                                          |
| ZW   | Filtek Z350 XT Flow and 0.016" stainless steel wire (A.J. Wilcock, Birmingham, UK) | Wire-composite splint                    | 1. Contour wire to dental arch                                                 |
|      |                                                                           |                                          | 2. Etch with 35% phosphoric acid (30 s)+wash+air-dry                           |
|      |                                                                           |                                          | 3. Bond+light-cure (10 s)                                                      |
|      |                                                                           |                                          | 4. Fix wire using flowable composite                                            |
|      |                                                                           |                                          | 5. Light-cure (10 s)                                                          |
| CW   | Ortho Connect Flow (GC) and 0.016" stainless steel wire (A.J. Wilcock)    | Wire-composite splint                    | 1. Contour wire to dental arch                                                 |
|      |                                                                           |                                          | 2. Etch with 35% phosphoric acid (30 s)+wash+air-dry                           |
|      |                                                                           |                                          | 3. Fix wire using flowable composite                                            |
|      |                                                                           |                                          | 4. Light-cure (10 s)                                                          |

*Bonding was performed using Adper Single Bond 2 (3M ESPE; Lot number: NA56773)

Fig. 1  Dental trauma splints used in this study.  
(a) Model without splint, (b) splint using either a control resin composite ZF or tooth fixation resin composites GF and LF, (c) wire-composite splint using a wire with either a control composite resin ZF or an orthodontic composite adhesive CF. ZF: Filtek Z350XT Flow; GF: G-Fix; LF: Light Fix; CF: Ortho Connect Flow.

Fig. 2  Periotest measurement scheme used in this study.

Periotest procedures, the splints were removed carefully and completely.

The flexural strength of each composite material was determined by ISO Standard-4049, with the metal mold substituted by an acrylic mold (Fig. 3a). Using the mold, ten specimens per each splint material were fabricated. A thin layer of detergent was applied along the insides of the mold for easy detachment after polymerization. The mold was placed between two slide glasses of 1 mm thickness to ensure proper morphology at all faces of the specimen. The composite materials were filled within the mold and polymerized by a LED curing unit (Elipar DeepCure-S, 3M ESPE), with a tip diameter of 10 mm and light intensity of 960 mW/cm² measured by a dental radiometer (LED Radiometer, Kerr, Middleton, WI, USA), for 40 s (10 s each time; four times along the length with 5 mm of overlap in between) on both top and bottom faces. The specimens were then separated from the mold and carefully trimmed with a carbide paper (Silicon Carbide Grinding Paper, Metallurgical Supplies, Tonawanda, NY, USA). They were stored in distilled water at 37°C for 24 h. Then, the flexural strength was measured by a three-point-bending test using a universal testing machine (Instron 8848, Instron, Norwood, MA, USA, Fig. 3a). The widths and heights...
of the specimens were measured immediately prior to testing. The distance between the two supports was 20 mm, and the crosshead speed was 1 mm/min. After measurement, the flexural strength, \( F \), was calculated using the following equation:

\[
F = \frac{3PfL}{2WH^2} \text{ (MPa)}
\]

where \( Pf \) is the maximum load in N, \( L \) is the distance between the supports in mm, \( W \) is the width of the specimen in mm, and \( H \) is the height of the specimen in mm.

The elastic modulus was also determined using the three-point-bending test described above. Elastic modulus, \( E \), was calculated using the following equation:

\[
E = \frac{\delta_f}{\delta_y} \times \frac{L^3}{4WH^3} \text{ (GPa)}
\]

where \( \frac{\delta_f}{\delta_y} \) is the change in force (\( \delta_f \)) per unit change in deflection at the center of the specimen (\( \delta_y \)) in N/mm, \( L \) is the distance between the supports in mm, \( W \) is the width of the specimen in mm, and \( H \) is the height of the specimen in mm.

The compressive strength and the diametral tensile strength of each composite material was measured according to a previous study\(^{21}\). Using a Teflon mold, ten specimens per each splint material were prepared. The specimens were fabricated and polymerized using the same methods and LED curing unit as in the flexural strength experiments. In the case of compressive strength specimens, specimens were polymerized in three 2.0 mm increments for 40 s (10 s after each increment, 10 s additionally at the bottom face). Diametral tensile strength specimens were polymerized for 20 s (10 s each time; top and bottom faces). Compressive strength and diametral tensile strength were measured using a universal testing machine (Instron 8848, Instron, Figs. 3b and c). The diameters and heights of the specimens were measured immediately prior to testing. The crosshead speed was 0.5 mm/min. After measurement, the compressive strength was calculated by dividing the failure load by the cross-sectional area. The diametral tensile strength (DTS) was calculated using the following equation:

\[
\text{DTS} = \frac{2F}{\pi DT} \text{ (MPa)}
\]

where \( F \) is the fracture load in N, \( D \) is the diameter in mm, and \( T \) is the height in mm.

For analysis, the six upper anterior teeth and first premolars were regrouped according to their functional homogeneity as upper central incisors (UCI), upper lateral incisors (ULI), upper canines (UC), and upper premolars (UPM). Statistical comparisons of Periotest values for labial, palatal, and occlusal pressure were performed for each tooth type for all groups. Comparisons among groups of flexural strength, elastic modulus, compressive strength, and diametral tensile strength of the tested composite were also performed. If parameters followed a normal distribution after checking with the Kolmogorov-Smirnov test, the values of the parameters in each group were compared by ANOVA, and the homogeneity of variance was tested with Levene’s test. According to the results of Levene’s test, post hoc comparisons were performed using either Tukey’s HSD or Dunnett’s T3. If parameters did not follow a normal distribution, they were analyzed using Kruskal-Wallis tests and Mann-Whitney \( U \)-tests with Bonferroni’s correction. All statistical analyses were performed with an alpha significance level of 0.05 using SPSS 23 (IBM SPSS Statistics, New York, NY, USA).
RESULTS

Measurements for labial and palatal pressure were not available for UCI, which simulated avulsed teeth, since the Periotest is unable to measure mobility beyond 50. UCI had the highest value in occlusal pressure. When ZW or CW was applied, the Periotest values were significantly reduced in labial and palatal pressure compared to no fixation, whereas in occlusal pressure they did not decrease significantly. Though ZW was more flexible than CW in the palatal pressure measurements of UCI, ZW and CW showed no significant differences in flexibility in labial or occlusal pressure. When LF, GF, or ZF was applied on UCI, the values significantly decreased, representing the rigidity of splinting. Among LF, GF, and ZF of UCI, only LF showed significantly

Table 2  Information about composites according to the manufacturers

| Composite                  | Organic matrix                                                                 | Filler                                                                                                               | Shade | Lot number |
|----------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-------|------------|
| Filtek Z350XT Flow         | Bis-GMA, TEGDMA, Procylat K                                                    | 46% of the volume.                                                                                                      |       |            |
| (3M ESPE, St. Paul, MN, USA)|                                                                                 | Yttrium fluoride: 0.1 to 5.0 μm, silica: 20 nm, zirconia: 4 to 11 nm, zirconia/silica clusters: 0.6 to 10 μm     | A2    | NC13892    |
| G-Fix                      | Phosphoric ester monomers                                                       | 26% of the volume.                                                                                                      |       |            |
| (GC, Kasugai, Japan)       |                                                                                 | Barium glass silane-treated powder, silica powder                                                                      | Clear | 1707182    |
| Light Fix                  | Methacrylic acid ester (UDMA, 4-META), acrylic acid ester, photo initiator      | None                                                                                                                 |       |            |
| (Sun Medical, Moriyama, Japan)|                                                                              | Barium glass silane-treated powder, silica powder                                                                      | Clear | SS11       |
| Ortho Connect Flow         | Phosphoric ester monomers, phosphoric acid, aluminum oxide, purified water, pigment | 26% of the volume.                                                                                                      |       |            |
| (GC)                       |                                                                                 | Barium glass silane-treated powder, silica powder                                                                      | Clear | 2005141    |

Table 3  Mean Periotest values and standard deviations (SD) of groups

| Group   | No fixation | ZW         | CW         | LF         | GF         | ZF         |
|---------|-------------|------------|------------|------------|------------|------------|
| Labial pressure |      |            |            |            |            |            |
| UCI     | >50.00 (N/A) | 34.31 (10.83) | 35.88 (11.19) | 3.64 (2.24) | 3.29 (2.00) | 2.52 (1.49) |
| ULI     | 9.85 (4.43) | 7.79 (4.21) | 9.42 (4.56) | 3.21 (2.34) | 1.61 (1.54) | 1.82 (2.13) |
| UC      | 8.93 (4.47) | 6.42 (3.94) | 6.58 (3.52) | 4.18 (3.74) | 1.97 (2.62) | 3.30 (3.51) |
| UPM     | −0.24 (3.87) | −0.24 (3.58) | −0.43 (3.44) | −0.24 (3.91) | −0.29 (3.57) | −0.24 (3.85) |
| Palatal pressure |     |            |            |            |            |            |
| UCI     | >50.00 (N/A) | 35.60 (4.95) | 31.52 (5.45) | 3.83 (2.08) | 3.07 (1.83) | 2.12 (1.61) |
| ULI     | 8.36 (6.15) | 6.67 (4.50) | 6.67 (5.34) | 2.70 (1.88) | 1.21 (2.19) | 0.48 (2.06) |
| UC      | 4.85 (3.66) | 4.36 (2.66) | 4.82 (2.66) | 2.73 (2.00) | 1.55 (2.27) | 0.70 (2.57) |
| UPM     | −3.29 (2.17) | −2.57 (2.29) | −3.24 (2.41) | −3.00 (2.57) | −3.24 (2.32) | −1.90 (2.72) |
| Occlusal pressure |     |            |            |            |            |            |
| UCI     | 28.17 (8.65) | 23.48 (6.21) | 23.33 (5.53) | 1.33 (1.18) | 0.43 (1.23) | 0.24 (0.91) |
| ULI     | 7.27 (2.94) | 6.12 (2.57) | 7.18 (2.65) | 0.48 (1.60) | −0.33 (1.29) | −0.42 (1.23) |
| UC      | 6.45 (3.24) | 4.36 (2.40) | 5.12 (2.62) | 1.91 (2.38) | 0.52 (1.95) | 0.88 (1.41) |
| UPM     | −4.57 (1.43) | −4.38 (1.66) | −4.62 (1.56) | −4.62 (1.47) | −4.33 (1.68) | −3.86 (2.03) |

Values with the same superscript are not significantly different when compared with rows ($p > 0.05$).
UCI: upper central incisors; ULI: upper lateral incisors; UC: upper canines; UPM: upper premolars; ZW: Filtek Z350XT Flow and 0.016” stainless steel wire; CW: Ortho Connect Flow and 0.016” stainless steel wire; LF: Light Fix; GF: G-Fix; ZF: Filtek Z350XT Flow
higher flexibility in occlusal pressure, but otherwise the flexibility did not significantly differ among them. For ULI and UC, the general tendencies were similar except that their values were smaller than those of UCI, as they were intended to represent normal teeth. UPM was screwed onto the model for the control group, and therefore showed constant values throughout experiments (Table 3).

For the mean flexural strengths, ZF had the highest value of 140.4 MPa, while LF had the lowest value of 69.84 MPa. GF, and CF had intermediate values of 88.79 MPa and 89.84 MPa, respectively, which were not significantly different (Fig. 4a). Regarding the mean elastic modulus, ZF retained the highest value of 7.268 GPa, while LF, GF, and CF had significantly lower values. The values for LF, GF, and CF were not significantly different (Fig. 4b). For the mean compressive strength, LF was significantly lower than GF, CF, and ZF, with a value of 199.1 MPa (Fig. 4c). GF, CF, and ZF were not significantly different. In the case of mean diametral tensile strength, LF had a significantly higher value of 137.4 MPa than GF, CF, and ZF (Fig. 4d). GF/CF and CF/ZF were not significantly different from each other.

**DISCUSSION**

The first null hypothesis, that a splint using new orthodontic composite adhesive would not differ in performance from conventional wire-composite splints was accepted. Although the chemical components and mechanical properties of the composite resins were different, ZW and CW did not show differences in mobility except for UCI under palatal pressure. This suggests that the major splinting effect of a wire-composite splint is mainly derived from the wire and not from the composite, as ZW and CW used the same wire. The thickness of the composite might explain why ZW and CW differed only in palatal pressure. There was an effort to apply consistent amounts of composite, but the thickness of composite was not completely controlled although other factors such as the area of composite application and position of the wires were fixed. If the composite was thinner, mobility might have been increased due to reduction in fixation, and this was seen in only one case in measurements of ZW of UCI in palatal pressure.

The second hypothesis, that a splint using new resin composites would not differ in performance from conventional resin splints, was accepted. Unlike ZW and CW, in which there was no wire as in LF, GF, and ZF, the mobility of UCI did not differ throughout, except for LF in occlusal pressure. In the absence of wire, the splinting effect may have been most influenced by the components of the resin composites. Considering the components of the resin composites, it was remarkable that only LF did not contain any filler. Since filler is usually included to obtain higher mechanical properties such as flexural strength, flexural modulus, and hardness, the higher flexibility of LF, as was occasionally observed, might be due to the absence of filler.

The third hypothesis, that there is no difference in the flexural strength, elastic modulus, compressive strength, and diametral tensile strength of new resin composites and orthodontic composite adhesives compared to conventional resin composites, was rejected. Flexural strengths and elastic moduli were significantly lower in LF, GF, and CF compared to ZF; in terms of flexural strength, LF had even smaller values than GF and CF. This phenomenon might also be explained by filler composition. Previous observations that filler increases flexural strength and flexural modulus of composites are consistent with the results of this study. ZF had the highest filler composition of 46% and thus had the highest flexural strength and elastic modulus. GF and CF had a filler composition of 26% and had the second highest flexural strength and elastic modulus. LF, which had no filler, showed the lowest flexural strength and elastic modulus. With regard to compressive strength and diametral tensile strength, it was observed that LF had significantly lower and higher values, respectively, implying its higher flexibility, which might also be explained by its different chemical composition. In compressive strength and diametral tensile strength, it was noticeable that GF and CF had similar or equivalent properties to ZF, which suggest that these composites have the capacity to withstand loads tending to reduce size or elongate comparable to the conventional flowable resin composite.
Although ZF had a much higher flexural strength and elastic modulus than the other resin composites used in this study or higher compressive strength and lower diametral tensile strength than LF, its rigidity was not clearly manifested when applied to the teeth. For example, Periotest values did not differ among the ZF, GF, and LF groups of UCI, except for LF in occlusal pressure. Similarly, Periotest values did not differ between the ZW and CW of UCI groups, except under occlusal pressure. The differences in mechanical properties may have been too small to be clinically significant. However, even if there were no differences between groups, this result implies that since GF, LF, and CW allow omission of the adhesive stage, GF/LF and CW might be reasonable alternatives to ZF and ZW, respectively. GF, LF, and CW potentially offer increased procedural convenience in the clinical environment.

In comparisons of labial and palatal measurements of UCI, the palatal measurements were always lower except for ZW and LF. When measured from the labial side, the tapping rod was aligned parallel to the occlusal surface as it contacted the tooth perpendicular to the surface. However, since the central incisors have palatal surfaces that are sloped toward the palate, the tapping rod was oriented more toward the alveolar process when applied to the palatal side. As the palatal tapping pressure was greater on the alveolar bone than in labial measurements, the values might have been lower.

The UCI of the ZW and CW groups, which were the most flexible, had high standard deviations in Periotest values, whereas the other groups had much smaller values. The Periotest machine has an intrinsic limitation in that its measurements require tapping motions toward the teeth. Therefore, the measurement values are variable both for more flexible splints and for more mobile teeth, potentially causing inaccuracies in measurement.

Another limitation was that this study utilized an in vitro model with acrylic teeth. Although gingiva, tooth socket, and periodontal ligaments were simulated with silicon and acrylic dentiform being supported by Periotest values, this model might not have completely reproduced the conditions of the oral cavity. Since tooth mobility is determined by holistic interactions between the bone, gingiva, periodontal ligament, and other structures, minute changes and physiological variations in mobility may not be fully reflected in measurements. Thus, although this study focused on relative comparisons among groups, uncertainties might remain due to limitations of in vitro measurements.

It was found that mobility measured by Periotest was level III for ZW and CW but level I in ZF, GF, and LF for UCI in this study. Keeping in mind the limitations of an in vitro study, these results imply that CW might be useful for flexible splinting and that GF and LF might be considered more suitable for rigid splinting. According to the IADT guidelines, flexible splints are recommended to be applied to avulsed and replanted teeth for two weeks\(^5\). Thus, in such cases, either ZW or CW might be recommended following dentist preferences regarding adhesive strategy. ZF, GF, and LF retain potential since there are cases where rigid splints are necessary. In cases of severe trauma accompanying alveolar or jawbone fractures, rigid splints should still be considered and applied for four weeks\(^6\).

In this study, tendencies and mobility changes were analyzed. However, despite repeated measurements, perfectly consistent data were not obtained. In the process of model fabrication, manipulations such as wire bending, plantation in silicone, and sectioning of teeth may have introduced variables. Future in vitro studies should more carefully control these variables. In addition, evaluations of discoloration and biodegradation of these new materials were not included in this study, and future studies will be needed to clarify the stability of these materials. Additionally, we performed mechanical tests only using an LED unit as a light curing source. In the future, it would be possible to discover differences in the mechanical properties of these new materials depending on different light curing units including diode-pumped solid-state lasers\(^13\).

CONCLUSION

ZW and CW might both be effective flexible splint options for avulsed teeth, whereas LF and GF are better choices for more rigid splints. CW and LF/GF are simpler alternatives to ZW and ZF, respectively, due to the omission of several bonding procedures.

ACKNOWLEDGMENTS

This research was supported by a National Research Foundation of Korea grant (NRF-2018R1A5A2024418) funded by the Korean government (Ministry of Science and ICT).

REFERENCES

1) Kwan SC, Johnson JD, Cohenca N. The effect of splint material and thickness on tooth mobility after extraction and replantation using a human cadaveric model. Dent Traumatol 2012; 28: 277-281.
2) Bourguignon C, Cohenca N, Lauridsen E, Flores MT, O'Connell AC, Day PF, et al. International Association of Dental Traumatology guidelines for the management of traumatic dental injuries: 1. Fractures and luxations. Dent Traumatol 2020; 36: 314-330.
3) Kehoe JC. Splinting and replantation after traumatic avulsion. J Am Dent Assoc 1986; 112: 224-230.
4) Andersson L, Lindskog S, Blomlof L, Hedstrom KG, Hammarstrom L. Effect of masticatory stimulation on dentoalveolar ankylosis after experimental tooth replantation. Endod Dent Traumatol 1985; 1: 13-16.
5) Day PF, Flores MT, O’Connell AC, Abbott PV, Tsilingariadis G, Fouad AF, et al. International Association of Dental Traumatology guidelines for the management of traumatic dental injuries: 3. Injuries in the primary dentition. Dent Traumatol 2020; 36: 345-359.
6) Berthold C, Auer FJ, Potapov S, Petschelt A. Influence of wire extension and type on splint rigidity —evaluation by a dynamic and a static measuring method. Dent Traumatol 2011; 27: 422-431.
7) Oikarinen K. Tooth splinting: A review of the literature and consideration of the versatility of a wire-composite splint. Endod Dent Traumatol 1990; 6: 237-250.
8) Ebeleseder KA, Glockner K, Pertl C, Stadtlater P. Splints made of wire and composite: an investigation of lateral tooth mobility in vivo. Endod Dent Traumatol 1995; 11: 288-293.
9) Sobczak-Zagalska H, Emerich K. Best splinting methods in case of dental injury —A literature review. J Clin Pediatr Dent 2020; 44: 71-78.
10) Mazzoleni S, Meschia G, Cortesi R, Bressan E, Tomasi C, Ferro R, et al. In vitro comparison of the flexibility of different splint systems used in dental traumatology. Dent Traumatol 2010; 26: 30-36.
11) Andreasen JO, Andreasen FM, Andersson L. Textbook and color atlas of traumatic injuries to the teeth: John Wiley & Sons; 2018.
12) De Santis R, Gloria A, Maietta S, Martorelli M, De Luca A, Spagnuolo G, et al. Mechanical and thermal properties of dental composites cured with CAD/CAM assisted solid-state laser. Materials 2018; 11: 504.
13) De Santis R, Russo T, Gloria A. An analysis on the potential of diode-pumped solid-state lasers for dental materials. Mater Sci Eng C Mater Biol Appl 2018; 92: 862-867.
14) Froes-Salgado NRD, Gajewski V, Ornaghi BP, Pfeifer CSC, Meier MM, Xavier TA, et al. Influence of the base and diluent monomer on network characteristics and mechanical properties of neat resin and composite materials. Odontology 2015; 103: 160-168.
15) Lovell LG, Newman SM, Donaldson MM, Bowman CN. The effect of light intensity on double bond conversion and flexural strength of a model, unfilled dental resin. Dent Mater 2003; 19: 458-465.
16) Von Arx T, Filippi A, Buser D. Splinting of traumatized teeth with a new device: TTS (Titanium Trauma Splint). Dent Traumatol 2001; 17: 180-184.
17) Berthold C, Thaler A, Petschelt A. Rigidity of commonly used dental trauma splints. Dent Traumatol 2009; 25: 248-255.
18) Shirako T, Churei H, Wada T, Uo M, Ueno T. Establishment of experimental models to evaluate the effectiveness of dental trauma splints. Dent Mater J 2017; 36: 731-739.
19) Winkler S, Morris HF, Spray JR. Stability of implants and natural teeth as determined by the Periotest over 60 months of function. J Oral Implantol 2001; 27: 198-203.
20) Laster L, Laudenbach KW, Stoller NH. An evaluation of clinical tooth mobility measurements. J Periodontol 1975; 46: 603-607.
21) da Silva Pereira R, de Bragança G, Vilela A, de Deus R, Miranda R, Veríssimo C, et al. Post-gel and total shrinkage stress of conventional and bulk-fill resin composites in endodontically-treated molars. Oper Dent 2020; 45: E217-E226.
22) Kim K-H, Ong JL, Okuno O. The effect of filler loading and morphology on the mechanical properties of contemporary composites. J Prosthet Dent 2002; 87: 642-649.