Development of optical guiding forceps for a direct bonding system using light-cured resin adhesives

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Multi-bracket systems are popular orthodontic appliances and are commonly bonded directly to enamel surfaces by resin adhesives. In light-cured bonding, the tip of the curing unit must be kept at a distance from the adhesive on the tooth, which can lead to low polymerization and insufficient bond strength. The curing lights also generate low-frequency electromagnetic fields, which can be harmful to patient health. Furthermore, bacterial contamination of the light-curing tips during use presents an infection risk for patients. In this study, we developed optical guiding forceps (OGFs) for polymerizing light-cured resin as a solution to these problems. With OGFs, polymerization of adhesives was deeper than with lower magnetic fields and the bonds had the same shear strength as those formed by conventional procedures. These results suggest that OGFs may have practical use in the direct bonding of orthodontic appliances as well as in provisional bonding.

Keywords: Polymerization depth, Shear bond strength, Low frequency magnetic field, Induced current, Carbon-to-carbon bond

INTRODUCTION

Numerous factors are involved in the polymerization of light-cured resin monomer, including light wavelength, irradiation intensity, exposure time, and the distance between the curing light guide-tip and the adhesive. The distance between the light-cured resin and the light source affects resin polymerization because the irradiance of a point light-source decreases as an inverse square function of distance. To counteract this effect, dental curing units are collimated and their working range is small, leading to a less acute decrease in irradiance with increasing distance. Nevertheless, light-emitting diode (LED) lights had lower power output at a distance of 10 mm (from the light tip to the radiometer) than halogen light units. In addition, for both LED and halogen lights, the mean hardness of the cured composites decreased as the distance from the light tip to the adhesive increased (from 2 mm to 9 mm). The depth of cure also decreased with increasing irradiation distance.

When orthodontic brackets and molar tubes are bonded directly to enamel surfaces using light-cure adhesives, it is difficult to irradiate with standard light-curing unit guide tips at a sufficiently close proximity. This is especially true at posterior teeth and with brackets held by forceps, because of space limitation in those areas of the oral cavity. The distance between the adhesive and the light guide-tip is important not only for bonding strength and polymerization depth, but also because of the low-frequency magnetic field emanating from the light-curing unit, which can be harmful to human health. Moreover, they induce electric currents in metallic appliances, causing metallic elements to elute from them, which can be a cause of metal allergy in patients. In addition, light-curing tips are prone to bacterial contamination after use, which elevates the risk of cross-infection in patients.

In this study, we have developed disposable optical guiding forceps (OGFs) to aid the polymerization of light-cured resin. By accurately guiding the light-tip, these were useful in bonding orthodontic appliances to enamel surfaces while minimizing the risks of the low-frequency magnetic field and infection. We describe the use of these OGFs (patent pending) in polymerizing light-cured resin, and demonstrate their potential usefulness in both provisional and permanent direct bonding of orthodontic appliances.

MATERIALS AND METHODS

Materials

For the OGFs, we used VH-001 (Mitsubishi Rayon Inc., Tokyo, Japan) as an acryl (polymethylmethacrylate) material, SGP-10 (PS Japan Inc., Tokyo, Japan) as a polyethylene, and Calibre™ 301-40 (Sumika Styron Polycarbonate Inc., Tokyo, Japan) as a polycarbonate plastic.

Two kinds of curing lights were used: Lightel-II (a halogen light with a cooling fan motor powered by a domestic power source; Morita Inc., Tokyo, Japan) and G-Light Prima (a rechargeable battery-powered LED light with no cooling fan motor; GC Inc., Tokyo, Japan). We also used orthodontic stainless steel (SUS) brackets (SUS304; SuperMeshBracket, medium twin bondable for mandible incisors; Tomy International
Inc., Tokyo, Japan) and orthodontic SUS wires (SUS304; Suzuki Stainless wire; Mitsuba Ortho Supply Inc., Tokyo, Japan). The cross-sectional size of these wires was 0.017×0.025 inches. A 30-mm length of this SUS wire was ligated to the brackets by elastomeric modules (polyurethane elastic ligature ties; Shofu Inc., Tokyo, Japan) for the induced current evaluation experiments\textsuperscript{10}.

For the evaluation of the OGFs compared with conventional procedures, we used LightBond light-cured resin adhesive (Reliance Orthodontic Products Inc., Itasca, IL, USA). This adhesive paste consists of 60–99% fused crystalline silica, 3–7% bisphenol A diglycidylmethacrylate, and 7–13% amorphous silica. Bovine mandibular incisors were purchased from the Yokohama Edible Meat Public Corporation (Yokohama, Japan). We created SUS jigs to mount and secure these teeth for the study of shear bond strength.

Development of OGFs for polymerization of light-cured resin

To determine the optimal shape of the OGFs, light from the Lightel-II curing light was transmitted through the shafts of the OGFs and any decrease in its transmission was evaluated using an illuminometer (LX2; Sanwa Electric Instrument Inc., Tokyo, Japan) in the dark room (Fig. 1). For this experiment, the OGFs were prepared using steel molds (DNAK80; Daido Steel Inc., Aichi, Japan) made by cutting and electrical discharge machining (Saito Mold Inc., Niigata, Japan). The shafts and complete OGF units were created by injection molding with the plastic materials listed above (Purako Inc. Niigata, Japan). We prepared OGFs with the shaft entrance diameter fixed at 8 mm (determined from the results of preliminary experiments; data not shown) and with a variable exit diameter (2, 4, 6, and 8 mm), length (90, 110, 130, and 150 mm) and tip angle (0, 5, 15, 30, and 45° at 30 mm from the tip) (Fig. 2A–C). After determining the shape of the OGF shafts, the body of the OGF was created by injection molding. Experiments were performed using light-cured resin adhesive (LightBond) cured by curing units (Lightel-II and/or G-Light Prima) with (“OGF”) or without (“conventional”) an OGF, with the distance between the resin adhesive and the light tip fixed at 10 mm. In transmitted light experiments using complete OGFs, decreases in the transmission of light through the OGFs was evaluated using an illuminometer in a dark room.

Measurement of magnetic fields and electric currents generated by curing lights via the OGFs

The magnetic fields and electrical current generated by each type of curing light was evaluated in orthodontic appliances by irradiating them with light through the OGFs. The distance from the curing light tip to the tooth surface was 111 mm for OGF procedures (110-mm shaft

Fig. 1  Schematic representation of experimental workflow.
Individual prototype OGF components created by injection molding.

A) Straight OGF shafts with 8-mm entrance diameter, 110-mm length, and various exit diameters (2, 4, 6, and 8 mm). B) Straight OGF shafts with 8-mm entrance diameter, 4-mm exit diameter, and various lengths (90, 110, 130, and 150 mm). C) OGF shafts with 8-mm entrance diameter, 4-mm exit diameter, and 110-mm length, with various tip angles (0, 5, 15, 30, and 45°).

Polymerized resin specimens after extracting unpolymerized resin.

A) Images show resin specimens polymerized at 10 mm. From left to right: polymerized by halogen light for 20 s with no OGF; polymerized by halogen light for 20 s with an OGF; polymerized by LED light for 10 s with no OGF; and polymerized by an LED light for 10 s with an OGF. B) Image shows a three-dimensional reconstruction of 3D scanning data from a specimen for evaluation of its volume. The specimen shown was polymerized by a halogen light for 20 s using an OGF.
in the specimen were C-C or C=C, and involved an NRS-3100 laser Raman spectrometer (JASCO Co., Ltd., Tokyo, Japan) with excitation wavelength of 532.06 nm at two regions (A and B) of each cured resin specimen after extraction of unpolymerized resin10 (Fig. 4A). Similar specimens (10 mm φ cylindrical shape with 2 mm thickness) cured for 30 min with a light irradiator for light-cured resins (effective wavelength: 400–600nm; αLight II N; J Morita Tokyo MFG Inc., Tokyo, Japan) were also analyzed. As positive controls, heat-cured MMA/PMMA resin samples (ACRON; GC Inc., Tokyo, Japan) and injection-molded PMMA plates (Mitsubishi Rayon Inc., Tokyo, Japan) were also analyzed. Each analysis was conducted according to a standard protocol15.

The results of Raman spectrometry were analyzed to calculate the percentage of C-C bonds (1450.4 cm⁻¹) among the total carbon-to-carbon bonds (C-C bonds plus C=C bonds (1638.4 cm⁻¹)) as an indicator of the polymerization rate.

**Estimation of shear bond strength of resin adhesives cured using OGFs**

Estimation of the shear bond strength was performed using a universal testing machine (AG-I; Shimadzu Co., Ltd., Kyoto, Japan) (Fig. 1). Bovine teeth (n=64) were stored at 4°C in 0.1% thymol solution, and used for experiments within 1 month of extraction. Before adhesion of brackets to the enamel surfaces, these bovine teeth were immersed for 24 h in Fusayama-Meyer artificial saliva16, which contains 0.4 g KCl; 0.4 g NaCl; 0.795 g CaCl₂; 0.78 g NaHPO₄; 0.005 g Na₂S·9H₂O; and 1 g NH₂CONH₂ (all reagents from Wako Pure Chemical Industries Inc., Tokyo, Japan) in 1 L of deionized distilled water at pH 5.3. Bovine enamel was etched using a 30-s treatment with the bonding agent (which contains phosphoric acid) before washing twice with distilled water. After air drying the etched enamel surface, orthodontic brackets were attached using light-cured resin adhesives irradiated with conventional procedures (irradiation distance: 10 mm; angle: 45° and 90°) or OGF procedures (irradiation distance: 111 mm; angle: 45° and 90°) (Fig. 5). Irradiation was done from...
two directions, each for either 10 s (G-Light Prima) or 20 s (Lightel-II) to ensure irradiation of both the upper and lower sides of the brackets at each irradiation angle. These bracketed bovine teeth were fixed to SUS jigs with self-curing resin (UNIFAST III, GC Inc., Tokyo, Japan) and were positioned with their adhesive surfaces parallel to the blade of a universal testing machine. Before evaluation of shear bond strength, specimens were immersed in artificial saliva for 24 h. Raw shear bond strength data (measured in Newtons (N)) were obtained. The area of the bracket base (excluding the mesh structure) was estimated from images using cell image analysis software (MiniMagics 2.0; Materialise Japan Inc., Kanagawa, Japan), and found to be (on average) 10.91±0.12 mm². The shear bond strength (in MPa) was then calculated by dividing the shear bond strength (N) by the average area of the bracket base (10.91 mm²).

Experimental conditions, data, and statistical analysis
Each experiment was repeated eight times, and the maximum and minimum values were excluded prior to analysis to eliminate the risk of errors from outliers. These remaining six values were used to calculate the mean±standard deviation (SD). Data were then analyzed using the Mann-Whitney U-test to reveal statistically significant differences between data sets.

RESULTS

Development of OGFs for polymerization of light-cured resin
From our preliminary results evaluating the light transmitted through the OGF shafts, we determined that the optimal OGF shaft shapes were a column or a cone (Fig. 1). First, we determined the entrance and exit diameters and shaft length that would be most appropriate for clinical use. From the results of our simulation of clinical use, we concluded that the best results were obtained with entrance and exit diameters and shaft lengths of 8 mm, <4 mm, and <130 mm, respectively. Thus, we fixed the entrance diameter of the OGF shaft at 8 mm for subsequent experiments. Transmitted light through the shafts was dramatically decreased at a 2-mm exit diameter, so we set this parameter at 4 mm (Fig. 6A). The effects of OGF shaft length on light transmission were then determined using these fixed entrance and exit diameter parameters. Light transmitted through the OGF shaft was decreased in direct proportion to the shaft length. From these results, we determined that the optimal shaft length was 110 mm (Fig. 6B). Finally, to optimize their clinical usefulness, we investigated the effects of the OGF tip angles on light transmission using the fixed entrance diameter, exit diameter, and shaft length parameters. Light transmitted through the shafts was decreased in direct proportion to the tip angle. We thus determined that the best tip angle was 0° (Fig. 6C). These optimization experiments were performed for all three materials (i.e., polycarbonate, polystyrene, and acryl...
(PMMA)). The rank order of the brightness of the transmitted light was: acryl>polycarbonate>polystyrene (Fig. 6A–C). Thus, for the main experiments in this study, we used acryl OGFs with an entrance diameter of 8 mm, and exit diameter of 4 mm, a shaft length of 110 mm, and a tip angle of 0°.

The complete OGFs were created to these dimensions by injection molding (Fig. 7A). To improve clinical usability and to allow better grip of small objects, we added a spacer component to the exit part of the OGFs, which protruded 1 mm from the OGF tips and thus maintained a 1 mm distance from the OGF tip to the target (Fig. 7A). Thus, the total distance from the light source to the target was 111 mm. Figure 7B shows the OGF in use. The light transmitted from the curing unit through the OGFs was \( \approx 95\% \) of that imparted by conventional procedures (Table 1). LED lights from the G-Light Prima unit suffered decreases in power output at 111 mm, but not 10 mm, compared with the Lightel-II halogen curing unit.

**Table 1** OGF transmission of light from light-curing units

| Distance (mm) | OGF | Transmitted light (k lux) | Lightel-II | G-Light Prima |
|--------------|-----|---------------------------|------------|---------------|
| 10           | −   | 379.3±9.22                | *          | 387.0±8.56    |
| 111          | +   | 360.2±9.85                | *          | 368.7±8.91    |

\( n=6; *p<0.05. \)

OGF: optical guiding forceps
**Fig. 8** Magnetic fields generated by curing units.
A) Magnetic fields generated by halogen curing unit with cooling fan. B) Magnetic fields from LED curing unit without cooling fan. The three panels in each part of the Figure represent different frequency ranges (see x-axis in each panel). Solid black lines indicate magnetic fields from curing units during irradiation at a 10-mm distance. Dotted black lines indicate magnetic fields from curing units during irradiation through 111-mm OGFs. Gray lines indicate magnetic fields from curing units switched off and non-irradiating at a 10-mm distance.

**Fig. 9** Voltage (A) and electric current (B) induced in orthodontic appliances by magnetic fields generated by the Lightel-II halogen curing unit at a distance of 10 mm.
Table 2  Electric voltage and current induced in orthodontic appliances by light-curing units used for light-cured resins

A. Induced voltage (µV)

| Irradiation | Distance (mm) | OGF | Lightel-II (halogen light with fan) | G-Light Prima (LED without fan) |
|-------------|---------------|-----|------------------------------------|-------------------------------|
| Off         | 10            | −   | 65.2±6.24                          | 37.5±3.87                     |
| On          | 10            | −   | 616.7±116.90                       | 383.3±98.32                   |
|             | 111           | +   | 133.3±25.16                        | 66.7±5.25                    |

B. Induced current (µA)

| Irradiation | Distance (cm) | OGF | Lightel-II (halogen light with fan) | G-Light Prima (LED without fan) |
|-------------|---------------|-----|------------------------------------|-------------------------------|
| Off         | 10            | −   | 44.7±5.16                          | 32.3±4.03                     |
| On          | 10            | −   | 583.3±75.28                        | 316.7±72.58                   |
|             | 111           | +   | 76.7±7.16                          | 51.2±8.48                    |

\(n=6; *p<0.05.\)

Main switches were turned on in the Lightel-II group.

OGF: optical guiding forceps

Table 3  Polymerization depths in resin adhesives achieved by light-curing units

| Distance (mm) | OGF | Lightel-II (halogen light with fan) | G-Light Prima (LED without fan) |
|---------------|-----|------------------------------------|-------------------------------|
| Irradiation (s) | 20  | 10                                |                               |

| Diameter (mm) | 10  | 4.9±0.03                          | 4.9±0.03                     |
|---------------|-----|-----------------------------------|------------------------------|
|               | 111 | na                                | na                           |
| Height (mm)   | 10  | 4.6±0.21                          | *                             |
|               | 111 | *                                 | 5.5±0.11                     |
| Weight (mg)   | 10  | 125.9±10.40                       | *                             |
|               | 111 | na                                | 156.5±4.68                   |
| Volume (mm³)  | 10  | 78.3±5.79                         | *                             |
|               | 111 | *                                 | 92.6±3.48                    |

\(n=6; *p<0.05.\)

na: data not available because the specimens were completely unpolymerized.

OGF: optical guiding forceps

(Table 3). PR was calculated in two regions, one at the base of the specimen (A) and one at its surface (B), where polymerization would be predicted to be higher. Indeed, the PR of region A was less than half that of region B, which was equivalent to specimens irradiated for 30 min. The PR of resin specimens cured with conventional and OGF procedures were comparable to each other in both regions. The PR of MMA solution was almost 2-fold lower than that of light-cured resin paste, and was also slightly lower than the value from region A of the...
Table 4 Percentage of C-C bonds in resin specimens, as a percentage of total carbon-to-carbon bonds, estimated by laser Raman spectrometry

| Resin                     | Condition                      | % of C-C to C–C + C=C |
|---------------------------|--------------------------------|-----------------------|
| Light-cured resin         | OGF procedure with G-Light Prima | Region A: 24.5±1.69   |
|                           |                                 | Region B: 55.2±1.99   |
|                           | Conventional procedure with G-Light Prima | Region A: 24.8±1.78   |
|                           |                                 | Region B: 55.3±2.01   |
|                           | 30 min light irradiation Paste  | Region A: 55.2±2.79   |
|                           |                                 | Region B: 18.2±1.80   |
| Acron heat-cured resin    | PMMA powder                     | 81.5±1.46             |
|                           | MMA solution                    | 10.2±1.60             |
| PMMA plate Injection molded product |                        | 97.4±1.75             |

n=6, *p<0.05.
OGF: optical guiding forceps

Table 5 Shear bond stress (MPa) of brackets adhered to teeth with resin adhesives polymerized by light curing units with and without OGFs

| Distance (mm) | Irradiation angle (°) | OGFs | Lightel-II (halogen light with fan) | G-Light Prima (LED without fan) |
|---------------|-----------------------|------|-------------------------------------|---------------------------------|
| 10            | 45                    | –    | 11.7±1.17                           | 12.4±1.04                       |
|               | 90                    | –    | 16.6±1.39                           | 17.0±1.48                       |
| 111           | 45                    | +    | 12.1±1.06                           | 13.4±1.42                       |
|               | 90                    | +    | 17.4±1.67                           | 19.2±1.78                       |

n=6, *p<0.05.
OGF: optical guiding forceps. Regions A and B were at the base and irradiated surface of the specimen, respectively (see text).

Estimation of shear bond strength of orthodontic brackets adhered with resin adhesives by light curing with OGF

The shear bond strength of the bracket-to-teeth bond imparted by OGF procedures was comparable to conventional procedures at equivalent irradiation directions (i.e., 45° and 90°) (Table 5). Irradiation at 90° was more effective than that at 45° for both conventional and OGF procedures. The shear bond strength of brackets secured with adhesives cured by LED light was comparable to that of brackets secured by resin cured using conventional procedures under the same irradiation conditions (Table 5).

DISCUSSION

For many decades, the multi-bracket system has been extremely popular. Before the development of this system, orthodontic appliances were secured to the tooth with metal bands, but the introduction of acid-etching of enamel and directly bonded brackets and molar tubes led to major changes in the practice of orthodontics. Direct bonding of attachments decreases gingival irritation, improves esthetics, facilitates better oral hygiene, eliminates the band from the interdental space, and decreases the potential for decalcification caused by leakage beneath bands. Direct bonding systems initially involved chemically cured resin adhesives, but these have been superseded by light-cured resins in recent times because of their superior handling and rapidity properties. However, to maximize bond strength with the enamel, it is important to maintain their position during curing. This can be challenging, especially in posterior areas where the already-limited space is further reduced by the bulkiness of the curing lamp tip. Moreover, the curing lights generate low-frequency electromagnetic fields that can be harmful to patients, both directly and indirectly through metallic corrosion of metal appliances due to the induced current, which can be a cause of metal allergy. In addition, light curing tips are prone to bacterial contamination during use, which increases the risk of cross-infection between patients. A widely-used measure for combating this contamination is the use of a transparent disposable barrier to cover the
curing light tip, but this reduces the efficiency of the light by 35–68%\(^{21,22}\). Alternative measures are autoclaving and polishing them after use\(^{23,24}\). We thus developed the OGFs to facilitate the accurate positioning of the brackets during polymerization of light-cured resin.

Preliminary experiments to determine the basic shapes of the OGFs were performed (Fig. 1), and illustrated that a combination of plastic guiding tips and metal forceps did not transmit sufficient light. We thus proceeded with all-plastic forceps. Various sizes and shapes of the entrance region (e.g., spherical, thick cylindered, convex lens-like, and concave lens-like) were tested, but were not effective at concentrating transmitted light. Various shaft shapes were also tested, and showed that basic shapes (e.g., columnar or cone shapes) were optimal for transmitting light. By combining these findings with the results shown in Fig. 6, we arrived at an optimal OGF that was made from all PMMA and had a conical shaft with an 8-mm entrance diameter, 4-mm exit diameter, and was 110 mm in length with no tip angle (Figs. 2 and 7). In our preliminary experiments to evaluate light transmission, we used only the Lightel-II halogen curing unit powered by a domestic power source because it is more stable than the rechargeable battery-operated LED unit, which was important during long time-course experiments. These preliminary experiments showed us that the exit diameter should be more than 4 mm, but 4 mm was maximum tolerable limit in the oral cavity, especially in the posterior region, so we fixed the OGF exit diameter at 4 mm.

Another important finding from the preliminary experiments was that curing efficiency was indirectly proportional to the distance between the curing lamp tip and the resin. Curing was best at closer proximity, so we designed a grip device into the OGF tips that protruded 1 mm to standardize this proximity, hence the total distance between the OGF entrance and the irradiated surface was 111 mm (Fig. 7). We also designed three guiding modules in the center of the shafts to counteract the twisting that tended to occur in the all-plastic devices (Fig. 7).

The optimized OGFs (as shown in Fig. 7) were created by injection molding using metal molds, and used for subsequent experiments. These complete OGFs were sufficiently efficacious to conclude that they would be useful not only for provisional bonding of appliances but also for direct bonding (Table 1). These conclusions are supported by our data regarding the polymerization depth and shear bond strength of brackets attached to the enamel surfaces by curing light transmitted through OGFs (Tables 3 and 5). The LED light brightness with a distance of 111 mm without OGFs was lower than with the OGFs, in keeping with the known characteristics of LED lights \(^{8}\) (Table 1).

The distance between the adhesives and the light guide tip is important not only for bonding strength and polymerization depth, but also for the negative effects of low-frequency magnetic fields emanating from the light unit. These low-frequency magnetic fields were detected during irradiation (Figs. 8 and 9; Table 2), as were currents through the appliance, which represent danger both by themselves\(^{8,9}\) and by the corrosive effects of metallic elution by these currents\(^{8,10}\). Low-frequency magnetic fields can pass through humans, buildings and most materials (i.e., glass, plastic, metals, and concrete\(^{9}\)) so are hard to block, but exposure is diminished by increasing the distance between the point source and the target \(^{59,59}\). The OGFs are an ideal way of extending this distance to 111 mm, which dramatically reduced the magnetic field and induced currents (Fig. 8; Tables 2, 3, and 5) while still causing effective polymerization (in contrast to light exposure at 111 mm with no OGF, where no polymerization was seen). The OGF procedures thus serve twin benefits of maximizing polymerization and minimizing harmful irradiation from the curing lamps.

Indeed, the resin specimens cured using OGFs were cured more deeply than those cured by conventional procedures using Lightel-II and G-Light Prima light sources (Table 2). The level of light-cure achieved with the OGF at 1 mm from the target was equivalent to that produced by both the halogen and LED lights at 10 mm without the OGF (Table 1). The area irradiated by the OGF was almost identical to the OGF exit area, whereas the area irradiated in conventional procedures at a 10-mm distance were much broader than the curing light tips. This suggests that the OGF does lose light during transmission but that this is balanced by the improved control and proximity gained by using it to focus the light where it is most useful.

In Bis-GMA and PMMA resin composites, the C=C bonds in the resin monomer are converted to C-C bonds during light-, chemical-, and heat-curing\(^{20}\). Our laser Raman spectrometry experiments included several positive controls using the G-Light Prima (Table 3). These showed us that the C=C and C-C bands were apparent at 1638.4 cm\(^{-1}\) and 1450.4 cm\(^{-1}\), respectively. Our carbon-carbon bond analysis confirmed the well characterized finding that resin polymerization decreases as an inverse function of distance\(^{15}\). Furthermore, the polymerization rates in cured resin specimens seemed low (55.2–55.3%) but were consistent across conventional and OGF procedures, indicating no qualitative difference in the resin curing (Tables 3 and 5). However, we did find a small artefact in our results whereby the light-cured resin paste was partially polymerized by irradiation from the laser beam at 532.06 nm during laser Raman measurement, which may account for a small discrepancy between the PR values of this material, region A of the resin specimens and the heat-cured MMA solution.

It is challenging to place the large curing light tips at 90° to the target, especially in the posterior areas of the oral cavity. For this reason, we attached brackets to enamel surfaces using light positioned at both 45° and 90° to the target for the shear bond strength experiments. We found that irradiation at 90° gave better bond strengths than at 45° in both conventional and OGF procedures. It is likely that the more oblique
angle reduces the amount of irradiation per unit area, which would affect the bonding strength, consistent with the results above describing the relationship between transmitted light brightness and polymerization depth. In this study, we developed disposable OGFs to transmit light from light-curing units at an optimal angle and without loss of curing efficacy, while minimizing electromagnetic fields and cross-infection risk factors that may be harmful to the patient. Our positive results demonstrate that these OGFs have great potential for both the provisional bonding of positioned appliances (to be followed by a definitive bonding step) and may also be sufficiently effective to eliminate the need for final bonding by achieving full and direct bonding themselves. We hope that these devices will prove useful to orthodontists using multi-bracket orthodontic systems attached to teeth via light-cured resin adhesives.

CONCLUSIONS

We developed OGFs for activating light-cured resins, and tested them as potential devices for facilitating the direct bonding of orthodontic appliances. The results obtained in this study are as follows.

1. The optimal OGF was made from PMMA and had a 4-mm exit diameter, 8-mm entrance diameter, and 110-mm length.
2. OGF bonding procedures eliminated the magnetic field exposure emanating from the curing units and thus reduced the electric currents induced in metal appliances.
3. The depth of polymerization in resin specimens cured by OGF procedures was slightly higher than by conventional bonding procedures.
4. The shear bond strength of orthodontic brackets attached to the enamel by OGF procedures was comparable to that by conventional bonding procedures.

We conclude that OGFs are useful for provisional bonding of positioned brackets prior to definitive bonding, and may even be sufficiently effective to produce definitive bonding themselves, allowing direct bonding of orthodontic appliances to enamel surfaces with light-cured resin adhesives without the attendant risk of electromagnetic radiation and infection. These devices will hopefully improve the experience of placing multi-bracket orthodontic systems for both patient and clinician.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Osamu Arasawa (Purako Inc., Niigata, Japan) for preparation of the prototype optical guiding forceps, and Ms. Yuko Amaki (Industrial Research Institute of the Niigata Prefecture, Niigata, Japan) for technical assistance and valuable advice in relation to laser Raman spectrometry. Creation of the metal molds for parts and complete OGFs used in this research was financially supported by Yumedukuri high-value support furthermore business (grant number 875; representative: Osamu Arasawa; suppliers of technology: Takashi Kameda, and Kazuo Okuma, August 2012–July 2013) by the Niigata industrial creation organization.

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