Rapid bonding and easy debonding of orthodontic appliances with 4-META/MMA-TBB resin using thermal heating

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4-Methacryloyloxyethyl trimellitate anhydride/methyl methacrylate-tri-n-butylborane (4-META/MMA-TBB) resin is widely used as a direct bonding adhesive for orthodontic appliances because of its strong bonding ability. However, its clinical disadvantages include long setting times and difficult debonding with subsequent residual adhesive left on the enamel surface. To resolve these problems, thermal heating was applied to orthodontic appliances. The setting time was dramatically reduced by thermal heating (160°C for 5 s), with the shear bond strength remaining the same as that stated in the manufacturer’s instructions. Debonding of appliances following thermal heating (160°C for 20 s) could be easily performed, decreasing the amount of adhesive left on enamel. These conditions were not accompanied by an increase in the heat pain threshold of pulpal dentin. These results suggest that the use of thermal heating in the bonding/debonding of 4-META/MMA-TBB resin may resolve its clinical weaknesses, making its ease of use similar to light-cured resin.

Keywords: Bonding, Debonding, Heat pain, 4-META/MMA-TBB resin adhesive, Positive temperature coefficient thermistors

INTRODUCTION

Direct bonding of attachments to the enamel surfaces 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 in multi-bracket orthodontic system¹. These direct bonding systems initially involved chemically cured resin adhesives, but these have been superseded by light-cured resins in recent times because of their superior handling properties and fast setting times. Although 4-methacryloyloxyethyl trimellitate anhydride/methyl methacrylate-tri-n-butylborane (4-META/MMA-TBB) resin adhesive retains the common disadvantages associated with usability of chemically cured resin adhesives, e.g., long setting time and complicated preparation, it is still widely used for bonding of orthodontic brackets because of its high bond strength²⁻⁰.

Adhesives for bonding of orthodontic brackets require not only sufficient bond strength to withstand masticatory and orthodontic forces, but also sufficient yield to allow debonding, because excessive bond strength usually results in intense pain⁰ and/or enamel fractures⁸ during debonding procedures. Strong bonding of the 4-META/MMA-TBB resin can cause such problems, including difficult debonding with residual adhesive left on the enamel surface following clinical treatment. To reduce discomfort and the clinical incidence of irreversible enamel surface damage, several methods of debonding brackets have been suggested, such as the use of ultrasonic instrumentation⁵, electrothermal heating⁶, Joule heating by electric current⁷, or laser irradiation⁸. Recently, heat-expandable microcapsules were reported for use in thermal debonding of appliances¹⁰⁻¹². However, there are still issues with debonding duration, insufficient bonding/debonding strength, and/or expense.

In terms of 4-META/MMA-TBB resin, the long setting time remains its major disadvantage aside from difficult debonding. To maximize bond strength to enamel, it is important to maintain the same position during curing⁰. Recently, a fast-setting monomer entered the market to fill this demand, however, it does not compare with the convenience and ease of use of light-cured resin.

In this study, we will suggest a solution for the aforementioned problems, which may allow both rapid bonding and easy debonding of 4-META/MMA-TBB resin adhesive by means of thermal heating.

MATERIALS AND METHODS

Materials

The bonding material used in this experiment was 4-META/MMA-TBB resin adhesive (Orthomite SuperBond, Sun Medical, Moriyama, Japan), which consisted of polymer and monomer components. We also used orthodontic stainless steel (SUS) brackets (SUS304; SuperMeshBracket, medium twin bondable for mandible incisors; Tomy International Inc., Tokyo, Japan). Bovine mandibular incisors were purchased from the Yokohama Edible Meat Public Corporation.

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Creation of thermal heating plate machine and unit
For the experiments involving temperature and setting time measurements of the resin adhesive, a thermal heating plate machine (heating plate size: 100×30 mm, and made in aluminium) was created using the plate-type positive temperature coefficient (PTC) thermistors (AS-140; Sakaguchi E.H. VOC Inc., Tokyo, Japan) with a temperature variable function between 100 and 200°C by a thermo-control unit (Fig. 1a). From the results of these experiments, we decided that the heating temperature allowed both rapid bonding and easy debonding of resin adhesive. The fixed temperature (160°C) heating unit for the shear bond strength tests was created in a compact size, usable in oral cavity (width×length×height: 15×150×10 mm, heating part: 5 mm diameter and 8 mm height, made in SUS304), using a cylindrical PTC thermistor (SA-060; Sakaguchi E.H VOC Inc., Tokyo, Japan) (Fig. 1b). PTC thermistors are resistors with a positive temperature coefficient, which means that the resistance increases with increasing temperature. In this experiment, we used the switching type PTC thermistors. When the switching type PTC thermistor is heated, the resistance starts to decrease at first, until a certain critical temperature is reached. As the temperature is further increased above that critical value, the resistance increases dramatically. This means that this type PTC thermistor plays roles of both heating unit and thermostat, which make heating machines/units small size and simple construction compared with the conventional ones.

Measurement of temperature changes and setting time of resin specimens under heating
To estimate the temperature rise of resin specimens during curing with thermal heating, we created disc-form resin adhesive specimens (shaped by a teflon mold of 10 mm diameter and 2 mm height, preheated at 37°C on the slide warmer (Fisher Scientific Inc., Waltham, MA, USA)), which were cured by the heating plate machine (Fig. 1a). The heating plate machine set the temperature from 100 to 200°C at intervals of 10°C. K-type thermocouple sensors were set at the heating plate and the resin specimens were set at the opposite side of heating plate, which made contact with the 37°C-set plate of the slide warmer (Fig. 2). K-type thermocouple sensors were connected to the digital multimeter (M-6000H; Metex Inc., Seoul, Korea) by Universal Serial Bus (USB) to the Windows personal computer (CF-S9; Panasonic Inc., Osaka, Japan), which recorded the data with T’s Digital Multi Meter Viewer software (http://www.ts-software-jp.net/products/tsdmview.html).

For evaluation of the setting time of the resin specimens during thermal heating, we used a Gillmore needle. When a Gillmore needle, weighing 1 pound with a 1/24 inch diameter tip, failed to indent the surface, this was recorded as the setting time by the process of Fig. 220).
Temperature measurement of bracket base, enamel surface, and pulpal dentin surface under curing with heating

Bovine teeth were sectioned longitudinally in the mesiodistal direction with a diamond disc saw (Isomet low speed saw model no.11-1280-170 with Buehler wafering blades; Buehler Inc., Lake Bluff, Illinois, USA), and put on the slide warmer set at 37°C. To estimate the temperature rise of the bracket base, enamel surface, and pulpal dentin surface during curing of the adhesive under heating, K-type thermocouple sensors were set at the bracket base (between the enamel of the bovine teeth and the bracket base) with curing resin adhesive, and the enamel (5 mm distance from bracket base) and pulpal dentin (beneath the bracket) surfaces were fixed with silicon adhesive (SILMATE82W-100; Momentive Performance Materials Japan, Tokyo, Japan) (Fig. 3). The heating plate machine set the temperature from 100 to 200°C at intervals of 10°C, and was used for heating of the resin adhesive. K-type thermocouple sensors were also connected to the digital multimeter by USB to the personal Windows computer, which recorded the data via the viewer software.

Determination of thermal heating conditions for rapid bonding and easy debonding of appliances

From the data on temperature changes of the resin adhesive, bracket base, enamel surface, and pulpal dentin surface in the above experiments, the optimal temperature and time for rapid bonding and easy debonding of appliances were established. In determining the optimal temperature, the reported heat pain threshold temperatures in the oral cavity 21,22 for comfortable bonding and debonding of appliances, setting time of resin specimens as long as light curing resin (10–20 s; we set this condition as 15 s) for rapid bonding of appliances by accelerating of polymerization of the resin adhesive, and glass transition temperature (Tg) of acrylic resin (PMMA) including 4-META/MMA-TBB resin23 for easy debonding of appliances by softening of the polymerized resin adhesive, were considered.

Measurement of tooth thickness beneath the brackets

After temperature measurement, the teeth were sectioned longitudinally through the bonding site with a diamond disc saw and the distance from the buccal enamel surface (midpoint of the resin beneath the bracket base) to the pulpal dentin surface was measured under a stereoscopic microscope (C-PS; Nippon Kogaku Inc., Tokyo, Japan) with a CMOS microscopic camera (130M; Artray Inc., Tokyo, Japan) (Fig. 4a). This was connected to a Windows personal computer for measurement.

Effects of thermal heating on shear bond strength of appliances adhered to enamel surfaces with resin adhesive

Estimation of the shear bond strength was performed using a universal testing machine (AG-I; Shimadzu Co., Ltd., Kyoto, Japan). Bovine teeth (n=64) were stored at 4°C in 0.1% thymol solution, and used for experimentation 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 saliva (AS), which contains 0.4 g KCl; 0.4 g NaCl; 0.795 g CaCl₂·2H₂O; 0.78 g NaHPO₄·2H₂O; 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. After immersion in AS, bovine teeth were fixed to SUS jigs with self-curing resin (UNIFAST III; GC Inc., Tokyo, Japan). Bovine enamel was etched using a 30-s treatment with the etching agent in the bonding agent set (65% phosphoric acid solution) before washing twice with distilled water. After air drying the etched enamel surface, orthodontic brackets were attached to the bovine teeth using 4-META/MMA-TBB resin adhesive with conventional bonding procedures (bonding method 820).
following the manufacturer’s instructions, without thermal heating) or thermal heating at 160°C for 5 s for bonding strength tests using the heating unit (Figs. 1b and 5). These bracketed teeth immersed in AS were placed in an incubator (Type FR12BS; Isuzu Seisakusho Inc., Tokyo, Japan) set at 37°C until use. These specimens were positioned with their adhesive surfaces parallel to the blade of a universal testing machine (Fig. 5). When 1 or 10 min had passed after starting the bonding procedure, shear bond strength tests were performed. For debonding tests, shear bond strength tests were performed using specimens (bracket-attached teeth with or without heating at 160°C for 5 s) heated at 160°C for 20 s for easy debonding after 24 h immersion in AS at 37°C (Fig. 5). Raw shear bond strength data (measured in Newtons (N)) were obtained. The shear bond strength (N) was then calculated by dividing the shear bond strength (N) by the average area of the bracket base (10.91 mm$^2$) estimated from 3D data obtained by a 3D digital scanner (Dental Wings 7 series; Dental Wings Inc., Montreal, Canada) using cell image analysis software (MiniMagics, version 2.0, Materialise Japan Inc., Kanagawa, Japan). After debonding, the adhesive remnant index (ARI) of resin adhesive on the bovine enamel surfaces was evaluated. The ARI score was assessed as follows; 0: no adhesive left on the tooth, 1: less than half of the adhesive left on the tooth, 2: more than half of the adhesive left on the tooth, and 3: all adhesive left on the tooth, with distinct impression of the bracket mesh.

Experimental conditions, data, and statistical analysis
All experiments were performed in the laboratory, which was maintained at a temperature of 22±1°C. 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 one-way ANOVA with Bonferroni’s post-test to reveal statistically significant differences between data sets.

RESULTS

Measurement of temperature changes and setting time of resin specimens under thermal heating
The temperature of all resin specimens undergoing thermal heating by the heating plate machine (temperature of heating plate parts was the preset temperature minus 20°C) were higher when compared with those of specimens following conventional bonding procedures (Tables 1a and b), because of heat radiation from the heating plate component (aluminum plate of 4×10 cm with 1-mm thickness) of the machine. The temperatures of the thermal-heated resin specimens were proportional to the heating time length and plate temperature (Table 1b). The setting times of thermal-heated resin specimens were inversely proportional to the heating time length and plate temperature (Table 1b). The thermal heating conditions of the resin specimens with the setting time shorter than 15 s (approximately 1/30 of setting time of the control group) were 5 s heating at >180°C, 10 s heating at >140°C, and 20 s heating at >120°C at the preset temperature (Table 1b). The heating condition of resin specimens with more than the Tg of PMMA (approximately 115°C) was not found (Table 1b). From these results, heating of resin specimens reduced the setting time of 4-META/MMA TBB resin.

Temperature measurement of bracket base, enamel surfaces, and pulpal dentin surfaces under curing with heating
After the experiments using resin specimens, temperature changes in the bracket base, enamel surface, and pulpal dentin surface under thermal heating were measured using bovine teeth and metallic orthodontic brackets. The temperature of each region in bracketed bovine teeth undergoing thermal heating rose in proportion to heating time length and plate temperature (Table 2). The thermal heating conditions when the bracket base temperature rose more than the Tg of PMMA (115°C) were 10 s heating at >200°C and 20 s heating at >160°C (Table 2). The thermal heating conditions when the enamel surface temperature rose more than the heat pain threshold of gingival tissue (47.9–48.3°C) were 5 s heating at >190°C, 10 s heating at <150°C, and 20 s heating at >110°C (Tables 2). The thermal heating condition when the pulpal dentin surface temperature rose more than heat pain threshold (47.7°C) was only 20 s heating at 200°C (Tables 2).
Table 1 Effects of thermal heating on the setting time of resin adhesive specimens using the heating plate machine

| Temperature of resin specimens (°C) | Setting time (s) |
|-------------------------------------|-----------------|
| 35.4 (1.2)                          | 468.2 (28.5)    |

n=6, ( ): SD. Specimens were placed on slide warmer at 37°C without heating by the heating plate machine.

b. Experimental groups

| Preset temperature (°C) | Plate temperature (°C) | Resin adhesive specimens | 5-s heating | 10-s heating | 20-s heating |
|-------------------------|-------------------------|--------------------------|-------------|--------------|--------------|
|                         |                         | Temperature (°C)         | Setting time (s) | Temperature (°C) | Setting time (s) | Temperature (°C) | Setting time (s) |
| 100                     | 84.1 (0.8)              | 41.4 (1.5)               | 51.6 (3.0)   | 46.2 (1.5)   | 29.6 (1.7)   | 69.4 (2.1)   | 29.2 (1.8)   |
| 110                     | 94.4 (1.1)              | 45.4 (1.1)               | 34.8 (3.4)   | 51.2 (1.3)   | 24.4 (2.2)   | 83.2 (0.8)   | 21.2 (1.7)   |
| 120                     | 102.4 (2.3)             | 52.2 (2.6)               | 26.4 (2.6)   | 60.6 (1.5)   | 19.6 (1.7)   | 86.6 (2.4)   | 15.2 (1.8)   |
| 130                     | 113.8 (2.4)             | 58.2 (0.8)               | 24.8 (1.3)   | 68.2 (1.5)   | 17.2 (2.4)   | 91.2 (1.5)   | 11.2 (1.3)   |
| 140                     | 125.6 (1.7)             | 62.2 (0.8)               | 22.4 (1.5)   | 71.6 (1.5)   | 15.2 (1.3)   | 94.8 (3.0)   | 6.2 (1.9)    |
| 150                     | 135.4 (2.4)             | 65.2 (2.3)               | 19.8 (1.5)   | 74.2 (2.7)   | 14.2 (1.8)   | 97.2 (1.1)   | 4.8 (0.8)    |
| 160                     | 146.8 (3.4)             | 67.6 (1.7)               | 18.8 (1.3)   | 76.4 (1.6)   | 12.4 (1.1)   | 99.6 (2.6)   | 3.6 (1.1)    |
| 170                     | 156.4 (1.8)             | 68.4 (2.2)               | 16.8 (0.9)   | 79.8 (1.3)   | 9.2 (0.8)    | 102.8 (2.6)  | 3.2 (1.3)    |
| 180                     | 166.8 (1.9)             | 70.2 (1.6)               | 15.2 (0.8)   | 81.6 (1.1)   | 8.2 (1.1)    | 104.8 (1.6)  | 1.8 (1.8)    |
| 190                     | 177.2 (3.6)             | 72.6 (2.7)               | 13.4 (1.1)   | 83.6 (1.8)   | 6.4 (1.5)    | 108.4 (1.7)  | 1.2 (1.3)    |
| 200                     | 185.4 (2.1)             | 74.2 (2.3)               | 12.4 (0.6)   | 84.6 (2.4)   | 4.8 (0.8)    | 113.2 (2.2)  | 0.6 (0.9)    |

n=6, ( ): SD. All data for experimental group were statistically significant when compared with data of control group (p<0.05). Specimens were placed on slide warmer at 37°C with heating by the heating plate machine.

Heat pain threshold of the oral cavity, the optimal temperatures for rapid bonding and easy debonding of brackets with 4-META/MMA-TBB resin were 5 s heating at 160°C and 20 s heating at 160°C, respectively (Tables 1 and 2). We thus created a 160°C-heating compact unit usable in the oral cavity (Fig. 1b). Actual temperature changes in the bracket base, enamel surface, and pulpal dentin surface under 160°C heating using this heating unit were also measured using bovine teeth and metallic orthodontic brackets. At 5 s heating, enamel and pulpal dentin surface temperatures were less than the heat pain threshold of gingiva and at pulpal dentin surface, respectively (Table 3). At 20 s heating, the bracket base temperature rose more than the Tg of PMMA (Table 3). The pulpal dentin surface temperature was less than the heat pain threshold at the pulpal dentin surface. However, the enamel surface temperature rose more than the heat pain threshold of gingiva (Table 3).

Measurement of tooth thickness beneath the brackets

After temperature measurement, the teeth were sectioned longitudinally through the bonding site and
Table 2  Temperature changes (°C) of bracket base, enamel surface, and pulpal dentin surface by thermal heating of metallic brackets adhered on enamel surfaces with the heating plate machine

| Preset temperature (°C) | Bracket base | Enamel surface | Pulpal dentin surface |
|-------------------------|--------------|----------------|------------------------|
|                         | Heating time (s) |                 |                        |
|                         | 5 10 20       | 5 10 20        | 5 10 20                |
| 100                     | 44.6 (2.3)    | 38.8 (0.9)     | 38.2 (0.8)             |
|                         | 54.1 (2.4)    | 43.2 (1.3)     | 39.6 (0.9)             |
|                         | 63.6 (3.1)    | 46.5 (0.9)     | 40.9 (0.8)             |
| 110                     | 52.1 (2.2)    | 39.8 (0.5)     | 38.6 (0.8)             |
|                         | 65.2 (2.4)    | 44.6 (0.9)     | 40.1 (0.9)             |
|                         | 75.2 (2.7)    | 48.2 (0.9)     | 41.6 (0.5)             |
| 120                     | 58.7 (2.1)    | 41.2 (0.8)     | 39.2 (0.8)             |
|                         | 76.3 (1.9)    | 45.4 (0.6)     | 40.7 (0.8)             |
|                         | 85.4 (3.1)    | 52.2 (0.9)     | 42.2 (0.6)             |
| 130                     | 64.4 (2.6)    | 41.8 (0.8)     | 39.4 (0.8)             |
|                         | 81.7 (2.6)    | 46.5 (1.1)     | 41.0 (0.8)             |
|                         | 97.4 (2.5)    | 53.9 (0.9)     | 42.6 (0.6)             |
| 140                     | 66.5 (2.7)    | 43.2 (0.9)     | 39.6 (0.8)             |
|                         | 89.6 (3.0)    | 47.9 (0.8)     | 41.8 (0.8)             |
|                         | 106.9 (4.4)   | 55.8 (1.5)     | 43.1 (0.9)             |
| 150                     | 69.1 (2.7)    | 44.6 (0.6)     | 39.8 (0.7)             |
|                         | 96.6 (3.5)    | 51.6 (1.1)     | 42.0 (0.8)             |
|                         | 110.4 (2.1)   | 57.9 (1.4)     | 43.8 (0.8)             |
| 160                     | 71.8 (1.9)    | 45.2 (1.0)     | 40.0 (0.8)             |
|                         | 100.3 (3.1)   | 53.1 (1.1)     | 42.2 (0.8)             |
|                         | 116.7 (3.9)   | 63.8 (1.3)     | 44.6 (0.9)             |
| 170                     | 76.2 (2.8)    | 46.2 (0.9)     | 40.2 (1.1)             |
|                         | 103.6 (2.6)   | 54.7 (0.9)     | 42.4 (1.1)             |
|                         | 123.7 (4.1)   | 68.8 (1.1)     | 45.5 (1.1)             |
| 180                     | 79.3 (2.3)    | 47.4 (0.6)     | 40.4 (0.9)             |
|                         | 108.0 (4.2)   | 56.2 (0.9)     | 42.6 (0.9)             |
|                         | 126.1 (3.7)   | 72.4 (1.2)     | 44.4 (1.2)             |
| 190                     | 85.4 (1.9)    | 48.4 (0.6)     | 40.6 (0.9)             |
|                         | 113.1 (2.6)   | 60.6 (0.9)     | 42.8 (0.9)             |
|                         | 128.4 (4.0)   | 75.9 (1.3)     | 47.4 (1.1)             |
| 200                     | 89.4 (2.5)    | 50.2 (1.1)     | 40.8 (0.8)             |
|                         | 116.8 (4.3)   | 62.8 (0.9)     | 43.1 (1.2)             |
|                         | 132.7 (3.8)   | 80.4 (1.2)     | 48.5 (1.1)             |

n=6, (): SD.

Table 3  Temperature changes (°C) of bracket base, enamel surfaces, and pulpal dentine surfaces by thermal heating of metallic brackets adhered on enamel surfaces with the heating unit

| Tip temperature of the heating unit preset at 160°C | Bracket base | Enamel surface | Pulpal dentin surface |
|---------------------------------------------------|--------------|----------------|-----------------------|
|                                                   | Heating time (s) |                 |                        |
|                                                   | 5 10 20       | 5 10 20        | 5 10 20                |
| 158.2                                             | 78.1 (1.6)    | 46.5 (0.9)     | 40.3 (0.6)             |
|                                                   | 104.2 (1.3)   | 55.2 (1.0)     | 42.4 (0.9)             |
|                                                   | 115.5 (1.2)   | 62.8 (0.8)     | 43.9 (1.1)             |

n=6, (): SD.

the distance from the buccal enamel surface (midpoint of the resin beneath the bracket base) to the pulpal dentin surface was measured (Fig. 4a). The thickness of enamel, dentin, and their combination were measured to be near average thickness, with good reproducibility (Fig. 4b).

Effects of thermal heating on shear bond strength of appliances adhered to enamel surfaces with resin adhesive

Measurement of the shear bond strength of brackets was performed for evaluation of the effects of thermal heating on rapid bonding and easy debonding. In conventional bonding groups (no thermal heating), adhesives were
not completely hardened at 1 min after bonding brackets to the teeth (Table 4). Heating at 160°C for 5 s allowed 1-min hardening, and the shear bond strength was equivalent to those at 10 min after conventional bonding. The shear bond strengths at 10 min and 24 h after bonding with thermal heating were almost the same, which was equivalent to conventional bonding at 24 h. After thermal heating for easy debonding (160°C for 20 s) to the 24-h bonded bracketed teeth with or without thermal heating for rapid bonding (160°C for 5 s), the shear bond strengths were dramatically decreased. From the results of the ARI, residual resin adhesive on the enamel was expected to remain after debonding in the 24-h bonded groups compared with those in the 10-min bonded groups (Table 5). In groups with thermal heating for rapid bonding, the ARI were the same in the 1- and 10-min bonded groups. Compared with the conventional debonded groups (debonding without thermal heating) after 24 h of bonding, residual resin on the enamel after debonding was expected to have reduced in groups with thermal heating for easy debonding.

**DISCUSSION**

The shear bond strength of orthodontic brackets bonded with modern bonding materials exceeded 6–8 MPa, thereby rendering sufficient strength for orthodontic treatment\(^{27-30}\). This guideline was based on a report that a minimum bond strength of 5.9–7.9 MPa allowed satisfactory clinical performance and successful clinical bonding in orthodontic treatment\(^{31}\). In direct bonding systems, light-cured resins are mainstream in recent times because of their superior handling properties and fast setting times. However, they have the issues of polymerization depth and remaining unpolymerized regions containing C=C bonds where the curing light does not reach\(^{25}\). Although possessing disadvantages in terms of usability, e.g., long setting time and complicated preparation, the 4-META/MMA-TBB resin adhesive, which can polymerize chemically in the regions where the light does not reach, is still widely used for bonding orthodontic brackets because of its high bond strength\(^{3-5}\). Conversely, enamel fractures are reported to occur with bond strengths as low as 9.7 MPa\(^{32}\).

As a countermeasure for the irreversible enamel
surface damage that may occur during debonding, several methods of debonding brackets have been suggested. One of them was thermal debonding, including the use of Joule heating and heat-expandable microcapsules. In preliminary experiments, we tried to use 2.4 GHz microwaves for induction heating of resin adhesive for rapid bonding; however, it seemed to be harmful for the patients’ health. We thus simply used thermal heating with PTC thermistors, and solved the contradictory problems, i.e., rapid bonding and easy debonding. As per the results of this study, we developed and suggested a method for both rapid bonding and easy debonding of 4-META/MMA-TBB resin adhesive using one device.

For the purpose of this experiment, we considered the following points; heat pain threshold in the oral region for comfortable bonding and debonding of appliances, same setting time of the resin adhesive as light curing resin for rapid bonding of appliances, and the Tg of PMMA for easy debonding of appliances by softening of the polymerized resin adhesive. The polymerization initiator of 4-META/MMA-TBB resin is tri-n-butyl borane (TBB). The data of heat activated condition of TBB could not be found, because of TBB is a basically room-temperature initiator. We thus referred to the setting time (<15 s) of 4-META/MMA-TBB resin specimens. The requirements for thermal heating for the above contradictory demands, i.e., rapid bonding and easy debonding, should consist of thermal heating conditions as follows; 1. pulpal dentin surface temperature lower than heat pain threshold in both bonding and debonding, 2. setting time of resin shorter than 15 s in bonding, and 3. bracket base temperature higher than Tg of PMMA in debonding. In the experiments measuring the temperature and setting time of the resin adhesive using bracketed teeth, we found the optimal temperature was 160°C, and the optimal thermal-heating time was 5 s and 20 s for bonding and debonding, respectively (Tables 1 and 2). At this point, we created the compact heating unit, which satisfied the above heating conditions and was usable in the oral cavity. We focused on the PTC thermistors, because a heater using this small thermistor did not require a thermostat and this would have complicated the electric circuit. Using the compact heater unit we created for thermal heating, the temperature of bracket bases, enamel surfaces, and pulpal dentin surfaces were measured. The temperature after thermal heating for rapid bonding (5 s) and easy debonding (20 s) met the aforementioned conditions except for the enamel surface temperature, which rose more than heat pain threshold of the gingiva. As one of the countermeasures for this, a silicon cap, which exhibited poor thermal conductivity, was placed to surround the heating block of the unit. Another countermeasure was the use of cool water/air spray immediately after heating of the bracketed teeth. After the experiments for temperature measurement, the teeth were sectioned longitudinally through the bonding site and the distance from the buccal enamel surface to the pulpal dentin surface was measured (Fig. 4a). The thickness of bovine teeth beneath the brackets was close to that of human teeth, and various other properties also resembled those of human teeth. Intrapulpal temperature increase of 5.5°C was reported to be caused pulps or pulp necrosis in 15% of monkey irritated teeth. Thermal heating of 160°C for 20 s for easy debonding elevated the temperature of bovine pulpal dentin surfaces by 43.9°C (6.9°C elevation). This elevation of temperature might be harmful for the pulp health. However, a previous report using both bovine deciduous teeth and human permanent teeth indicated that temperature increase of bovine deciduous teeth was approximately 2-fold compared to that of human permanent teeth at the same experimental conditions. Teeth thickness beneath brackets were almost same in bovine permanent teeth (Figs. 4a and 4b) and human permanent teeth. However heat conduct should be different among them. In this mean, we could not necessarily compare between bovine and human teeth. On the other hand, thermal heating condition for easy debonding, which might be harmful for bovine teeth, should not be always harmful for human teeth. Further studies about this point should be needed.

The shear bond strength of brackets was assessed for evaluation of rapid bonding and easy debonding with thermal heating using the aforementioned heating unit. In conventional bonding groups (group without thermal heating for rapid bonding), adhesives were not completely hardened at 1 min after bonding of brackets to the teeth (Table 4). Thermal heating of the appliances at 160°C for 5 s allowed 1-min hardening of the resin adhesive with a shear bond strength equivalent to those in the conventional bonding group after 10 min of bonding. These bond strengths were approximately 85% of the 24-h bonded groups with or without thermal heating. The shear bond strengths of the 10-min and 24-h bonded groups with thermal heating were almost the same, which were equivalent to those of the conventional bonding group after 24 h of bonding. These bond strengths, 15.9–18.6 MPa, by far exceeded the minimum bond strength for acceptable orthodontic treatment (>6–8 MPa), and for possible occurrence of enamel fractures during debonding (9.7 MPa). After thermal heating was applied for easy debonding (160°C for 20 s) to the 24-h bonded bracketed teeth with or without thermal heating for rapid bonding (160°C for 5 s), the shear bond strength, 3.9–4.1 MPa, dramatically decreased to the level of 21–22% of the 24-h bonded groups, and less than the required minimum bond strength for direct bonding (5.9–7.9 MPa). These results suggest that thermal heating of appliances may allow both rapid bonding with sufficient bond strength, and easy debonding with one compact heating unit. In addition, residual resin adhesive on the enamel surface might be reduced in quantity in the groups with thermal heating for easy debonding, when compared with the conventional debonding groups (debonding without thermal heating) at 24 h after bonding. This might be because of sufficient softening of the hardened resin adhesive by thermal heating at 160°C for 20 s, as the
adhesive stuck to the bracket base after thermal heating for debonding had elastomeric properties.

CONCLUSION

We developed thermal heating protocols for rapid bonding and easy debonding of orthodontic appliances adhered to the enamel surfaces with 4-META/MMA-TBB resin adhesive using a compact heating unit at a steady temperature. The results obtained in this study are as follows:

1. The optimal thermal heating condition for rapid bonding with 4-META/MMA-TBB resin adhesive was 160°C for 5 s, which reduced the setting time to 1/8th of the setting time when using the conventional bonding protocol.

2. The optimal thermal heating condition for easy debonding with 4-META/MMA-TBB resin adhesive was 160°C for 20 s, which reduced the debonding strength to 1/5th of that required during conventional debonding.

3. These optimal thermal heating conditions for rapid bonding and easy debonding were not accompanied by an increase in the pulpal dentin surface temperature to the heat pain threshold (47.7°C) without cooling after heating.

We conclude that the protocols of thermal heating for rapid bonding and easy debonding with a compact device are useful for safe, quick, and predictable orthodontic treatment using direct bonding in a multi-bracket system. These protocols with a heating device will hopefully improve the experience of placing and removing multi-bracket orthodontic systems for both patient and clinician.

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