Accuracy of Temporary Laser Welding of FPDs by Nd:YAG Laser in the Oral Cavity

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Received January 30, 2006/Accepted July 24, 2006

The purpose of this study was to investigate the accuracy of temporary fixation with laser welding for fixed partial dentures (FPDs). Five kinds of experimental FPD with different welding/soldering gaps were fabricated (0, 20, 50 μm for welding; 300 μm for soldering). Then, FPDs were temporary-fixed by laser welding or with a self-curing resin. Fixation accuracy was evaluated by the change in distance and the angular deformation between two retainers. The change in distance and the angular deformation between two retainers of the FPD without welding/soldering gap were significantly larger than the other FPDs (p<0.05). With due consideration to the displacement of teeth or implants especially in the mesiodistal direction, and by taking into account the inevitable errors of the indirect method, it seemed reasonable to provide a welding space of approximately 20 μm.

Key words : Nd:YAG laser, Temporary laser welding, Deformation

INTRODUCTION

Nowadays, the indirect method is the most commonly used technique for fabricating dental prostheses. In particular, long-span fixed partial dentures (FPDs) are more frequently used due to improvements in the quality of precise castings and in implant diffusion. However, it is rather difficult to fit a long-span FPD well into all abutment teeth. Therefore typically, a long-span FPD is divided into several units and each unit is cast separately. These units are then tried in the oral cavity and temporarily assembled by impression plaster or self-cured acrylic resin. Finally, they are fixed by soldering or laser welding.

With soldering, the heating of the whole assembly induces anisotropic thermal expansion and compressive deformation due to the release of internal stress — which has accumulated via the casting process. On the other hand, in laser welding, contraction of the base metal arises in the welded parts. Therefore, a strong and accurate fixation of the assembly is essential for minimizing this contraction.

There are many reports that pertain to temporary fixation of dental units by soldering; linear dimensional variability of soldering index materials, advantage of a reinforcement wire in temporary fixation with self-curing resin, effect of fixation strength on assembly accuracy, and the technique for taking soldering indices. But in 1960, Maiman made the earliest application of stimulated optical radiation in ruby to surgical management in medicine. Then in 1964, Goldman et al. made their first attempt to remove dental caries in an extracted tooth with laser irradiation. As for Gordon and Smith, they reported on their first experimental laser welding of dental alloys using Nd:Glass laser in 1970. Since then, research and development on laser welding for dental laboratories has been ongoing until today.

Presently, in Japan too, laser welding plays an active role in the manufacturing of fixed partial dentures and removable partial dentures. Laser welding is welding by aiming heat at a small point. This welding technique causes no damage to the surrounding parts and requires no investing. As this technique can be applied to various metals or alloys for dental use, laser welding is useful for making prosthetic appliances.

Conventional welding machines used in dental laboratory are able to produce a high-power pulse output — which leads to concerns about thermal injury to adjacent tissue due to accumulated heat. Against this background, it is not feasible to apply laser welding in the oral cavity. However, due to rapid changes and advancements in laser technology, a power pulse mode has been developed. With this pulse mode, it is possible to produce a high-energy output and perform a minimally invasive irradiation by alternating the irradiation between on and off states at short time intervals. Of the pulsed mode laser systems which have been developed, Nd:YAG laser is one which can weld alloys in the oral cavity.

From a basic odontological viewpoint, Shibuya et al. investigated the thermal effect on dental pulp and dentin when restorations were irradiated with laser in the oral cavity. They reported that the thermal change caused by laser welding was within 11°C.
This thermal change is said to be tolerable for the dental pulp. Further, super-pulsed Nd:YAG laser has been reported to be capable of removing metals such as dowels and dental reamers\(^ {15} \). However, concerning intraoral laser welding of restorations—such as fixation using orthodontic wires, temporary fixation of crowns and inlays for periodontal treatment, and repair of prostheses, few clinical reports are available\(^ {16} \). Therefore, the deformation of prostheses due to intraoral laser welding is not clear yet.

Hence, the purpose of this research was to estimate the deformation of fixed partial dentures when welded intraorally using laser, and thereby to search for the best fixation method with highly accurate laser welding or soldering.

**MATERIALS AND METHODS**

**Master die**
A metal die was machined from stainless steel (18-8 stainless steel, SUS303 and 304) (Fig. 1). Diameter of the second premolar at the cervical area was 8 mm and that of the second molar was 11 mm. Height of both abutments was 5 mm, taper was 6 degrees on either side of each abutment tooth, and marginal shape was a rounded shoulder with a width of 1.0 mm. Distance between centers of both abutment teeth was 21.5 mm. Mark-off lines were scribed in eight orientations, thereby dividing the entire circumference into 45-degree segments. Mark-off lines were used to make the position of the restoration coincide with that of the master die\(^ {17} \).

**Laser device**
A pulsed Nd:YAG laser system (an improved model of Power Pulse 1, SLT Japan Co. Ltd., Tokyo, Japan) was used in this study (Fig. 2). Wavelength of this laser light was 1.06 μm, pulse energy was 300-3000 mJ, repetition frequency was 1-10 pps, and pulse length was 1.2 ms. As the laser light was invisible, a red LED (wavelength: 0.67 μm) was used as the guide light. A dedicated quartz fiber (BAFE, SI type, SLT Japan; diameter: 600 μm, angle of divergence: 3 mrad) was used as the light guiding device (Fig. 2b).

**Specimen preparation**
1) Wax-up
The metal die was coated with one barrier layer (Seasir barrier, Dental alpha Co. Ltd., Osaka, Japan). A master wax pattern was made using an inlay wax (Green Inlay Wax Medium, GC Co., Tokyo, Japan) (Fig. 3). The pontic was plate-shaped, and the shape of the pontic’s connection area was an quadrangle of 3.5 mm × 3.5 mm. Impression of the master wax pattern was taken using an addition-cured elastomeric vinyl silicone impression material (Exafine Putty type, Regular type, GC Co., Tokyo, Japan), and a silicone mold was made to make wax patterns as identical as possible. The metal die was coated again with the barrier layer, and the silicone mold was filled with the inlay wax (Green Inlay Wax Medium, GC Co., Tokyo, Japan) and then pressed. Wax pattern made in this way was left on the metal mold at room temperature for more than six hours.
2) Cutting of wax specimen
Wax pattern was cut between the first molar (pontic) and the second molar with a heated scalpel (Disposable Scalpel, Feather Safety Razor Co. Ltd., Osaka, Japan.). Attention was paid to ensure minimal distortion to the retainers and pontic. Wax was

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Fig. 1 Master-die.

Fig. 2 Dental therapeutic laser:
(a) Laser device;
(b) Handpiece with silica-based fiber;
(c) Monitor.

Fig. 3 Master Wax Up.
then added to the cut space to adjust the welding space after it had been cast.

3) Investing
Retainers were removed from the master die and immediately invested (Cristobalite PF, Shofu Inc., Kyoto, Japan) according to manufacturer’s instructions. A ring liner (New casting liner, GC) was applied.

4) Casting
An Ag-Pd-Au alloy (Castwell MC 12% Gold, GC Co., Tokyo, Japan) was selected for this study. As health insurance covers FPDs made of Ag-Pd-Cu-Au alloy in Japan, it is thus a popular alloy material used for FPDs. After casting using a casting machine (Tiegelschleuder TS3, Degussa, Germany), specimens were cleaned using an ultrasonic cleaner (Ultrasonic3800, DENTCRAFT®) and oxide film was removed with a pickling agent for palladium alloys (Palla-clean, GC Co., Tokyo, Japan).

5) Adjustment of welding/soldering gap
Completed metal specimens were set up in the master die, and the marginal fit was checked. In this experiment, welding gaps of 0, 20, and 50 μm (LL0, LL20, and LL50) were chosen on the premise that the joint area was finally welded by laser after temporary laser fixation, and that soldering gap of 300 μm was chosen on the premise that the joint area was finally soldered after laser fixation (LS). In the control group (using the conventional method), a soldering gap of 300 μm was chosen assuming that soldering indices were taken using a self-curing resin (Pattern Resin, GC Co., Tokyo Japan) with a reinforcement wire (stainless steel, diameter: 3.5 mm) (RS).

In this study, the soldering gap was determined to be 300 μm because we took into consideration that soldering space was reduced having been partially joined by temporary laser welding, and that the fluidity of Ag-Pd-Au solder is inferior to that of gold solder. As a result, soldering gap employed in this study was larger than the generally recommended gap of 100-150 μm.

For base metal welding, laser welding space is generally preferred to be as small as possible. Thus, the three welding gaps employed in this study were set within 50 μm on the premise that welding was done with a normal pulse Nd:YAG laser. Each experiment group comprised six samples.

Each welding/soldering space was adjusted using thickness gauges (Thickness gauge No. 100, MK, Niigata Seiki Co., Niigata, Japan). Welding/soldering gaps were adjusted by carborundum point (Carborundum Point, Shofu Inc., Kyoto, Japan) using thickness gauges of 20, 50, and 300 μm respectively, and then polished with #800 waterproof abrasive paper. Following which, both connected and laser-irradiated parts were sandblasted with 50- μm alumina particles (High Blaster III, Shofu Inc., Kyoto, Japan) under two atmospheres.

6) Temporary fixation of connected parts by laser welding
Specimens of LL0, LL20, LL50, and LS groups were temporarily welded in a diagonal direction at four points using Nd:YAG laser (Fig. 4). Laser conditions were as follows: pulse energy of 3000 mJ, pulse frequency of 1 pps, pulse duration of 1.2 msec, welding time of 5 seconds, and focal length (i.e., distance between weld metal and tip of quartz fiber) of +0.1 mm per corner. Due to the thick welding gap of LS, pigmentum nigrum (Indian ink) was coated on the target part to enhance laser absorption sensitivity.

7) Temporary fixation by self-curing resin
Specimens of the control group (RS group) were temporarily fixed at the occlusal surface with a steel wire of 3.5-mm diameter for reinforcement and with...
a self-curing resin (Pattern Resin, GC). This fixation method was based on a report by Aoyama et al., whereby contraction percentage of the pattern resin was claimed to be less than that of other self-curing resins, and that the amount of distortion of the pattern resin with steel wire was smaller than that of pattern resin only.

8) Deformation of FPDs

A Micron Depth and Height Measuring Scope (KY-60, Nissho Optical Co. Ltd., Saitama, Japan) was used to measure the deformation of FPDs.

Test piece was fixed with vise keeping the margin side up (Fig. 5). Measurement began when the reader counter was reset at one point as the starting point. Coordinates were measured at 72 points at intervals of 5° along the outermost circumference of the marginal edge of second premolar and second molar until the starting point was reached again. In other words, each examination bridge had 144 measure points.

The virtual center and normal vector of the plane from the marginal edge of each retainer were calculated using the least squares method with the coordinates of the 72 points. Distance between the virtual centers of the retainers of second molar and second premolar was used to analyze the mesiodistal contraction (transverse contraction), and the normal vectors of these retainers were used to analyze the three-dimensional deformation of FPDs.

With the second molar of the master die, the virtual center was determined as the origin of the coordinate axes as follows: XY plane which included the margin of the second molar of the master die was established as the reference plane; Z axis corresponded to the normal vector of the second molar; and X axis, being perpendicular to Z axis, projected from the virtual center of the second molar to that of the second premolar (virtual center of second premolar was on XZ plane) (Fig. 6).

After fixation of FPDs, a virtual center point of each retainer was calculated by the least squares method from the coordinates of the 72 points. Then, all measurement points of each specimen were translated and rotated so that the normal vector of the retainer of the second molar corresponded to the reference axis (Z axis) and the virtual center of the second premolar was on the reference XZ plane.

After translation of the plane was completed, the angle consisting of the normal vectors of the two retainers was calculated to analyze the three-dimensional deformation. In addition, the projection angle to YZ plane of the angle which the normal vector of the second premolar made with X axis, and the projection angle to XZ plane of the angle which the normal vector of the second premolar made with Y axis were calculated. The former was buccolingual deformation, and the latter was mesiodistal deformation.

RESULTS

In this study, center distance of the master metal die was 21.5 mm. Obtained center distances of FPDs were 21.97 ± 0.17 mm in LL0, 21.49 ± 0.03 mm in LL20, 21.5 ± 0.02 in LL50, 21.48 ± 0.03 mm in LS, and 21.51 ± 0.03 mm in RS. Change in distance from the virtual center of the second molar to that of the second premolar was between 10 and 20 μm except for LL0 group. One-way ANOVA was applied and significant differences were recognized (p<0.05). Therefore, Tukey’s HSD method was used to determine which combinations were significantly different. It was found that there were significant differences between LL0 and the other groups (p<0.05).

Fig. 7 shows the spatial angle of the two normal vectors obtained in each condition in this experiment. Obtained angles were 65.91 ± 15.63 mrad for LL0, 5.50 ± 1.47 mrad for LL20, 9.61 ± 4.51 mrad for LL50, 11.35 ± 1.46 mrad for LS, and 11.17 ± 5.55 mrad for RS. Results in this study were tested by the Kolmogorov-Smirnov test, and regularity was not dismissed at the significance level of 0.05 for all groups. Therefore, Watson-Williams test was applied, where the five measured groups were used as factors and acquired data as induced variables. Significant differences in spatial angle at the
significance level of 0.05 were found in the combination of LL0 and all other groups and the combination of LL20 and LS.

Mesiodistal and buccolingual angles of rotation were calculated by the abovementioned method. Obtained mesiodistal angles of rotation were 39.38 ± 8.30 mrad for LL0, 2.48 ± 3.35 mrad for LL20, 5.13 ± 8.40 mrad for LL50, 0.01 ± 10.88 mrad for LS, and 6.25 ± 4.37 mrad for RS (Fig. 8). Obtained buccolingual angles of rotation were 52.61 ± 14.43 mrad for LL0, -0.18 ± 4.27 mrad for LL20, 2.61 ± 2.99 mrad for LL50, 0.18 ± 4.74 mrad for LS, and 1.40 ± 9.77 mrad for RS (Fig. 9). Statistical analysis of mesiodistal angles of rotation was done using the Watson-Williams test, and significant differences were found \((p < 0.05)\) in the combination of LL0 and all other groups. Significant differences in buccolingual angle of rotation were also found \((p < 0.05)\).

DISCUSSION

Measurement and analysis methods

There are two methods to measure the deformation of crowns and FPDs. One is to measure the gap between the master die and the restoration \([21-26]\); the other is to read the three-dimensional coordinates on the reference plane using a three-dimensional coordinate measuring machine or the coordinates at the points defined on the restoration, and then perform vector analysis \([27]\). The former method is easy in terms of visualizing marginal discrepancies, but it is inconvenient for the measurement of three-dimensional helical deformations. On the other hand, the latter method is well suited for detecting three-dimensional helical deformations because it can grasp three-dimensional shapes.

Three-dimensional coordinate measuring machines are classified as either contact type with a probe, or non-contact type without a probe. The Micron Depth and Height Measuring Scope used in this study was a non-contact type. Without a probe, this type of machine does not require any calibration of contact pressure or correction of measured value in view of the probe shape. Further, this machine utilizes superposition of emission lines from the projecting slit and the slit reference line, so measurement accuracy is higher than that of conventional non-contact measuring scopes. However, measurement accuracy is dependent on the observer’s experience. Therefore, to ensure the same level of measurement accuracy for this study, the authors measured all the six specimens of the same group on the same day after several measurement trials had been done.

With regard to the number of measuring points, the normal vector of each retainer could be derived using at least three coordinates. However, the specimens went through the processes of wax-up, investment, and casting, and the whole circumference of the margin was not always manufactured with the same dimensional accuracy. Therefore, the authors tried to eliminate the influence of these process errors by measuring as many points as possible.

Laser irradiation conditions

Maximum pulse energy of lasers commonly used in the dental treatment is below 900 mJ. As it is preferable that retainers of FPD are temporarily fixed as
tightly as possible, the maximum pulse energy of 3000 mJ was adopted in this study. In this case, to prevent heat accumulation due to the high pulse energy used, laser irradiation was conducted at a pulse rate of 1 pps using air cooling at the same time.

Deformation of temporary-fixed FPDs
Laser-irradiated FPDs showed transverse contraction and angular deformation. In this experiment, transverse contraction was present in mesiodistal deformation. Transverse contraction occurred orthogonal to the mesiodistal direction especially in the upper part of FPDs. This unbalanced contraction led to angular deformation, and caused the twisting of FPDs.

With the LL0 group, the transverse contraction value was significantly larger than those of other groups. This was attributed to the deformation of FPD in the mesiodistal direction (where the marginal side of specimen expanded and the occlusal side shrank), and that the virtual center moved toward the outer direction.

Concerning angular deformation, the mesiodistal deformation tended to be larger than the buccolingual deformation except for LL0 group — which had the largest amount of three-dimensional deformation. The large deformation in LL0 group (spatial angle, as well as mesiodistal and buccolingual deformation angles) was explained by following reason: it was practically impossible to place each part of retainer with no friction when FPD of LL0 was tried in the mouth. Each part of retainer might be displaced three-dimensionally when each retainer was fitted to the abutment tooth because two retainers were not completely butt-jointed without friction. It seemed like, therefore, with laser irradiation, a seesaw-like deformation occurred at the contact point (which acted as the fulcrum) such that the effects of laser welding could not be compensated by laser welding diagonally.

It is said that a narrower welding space would yield a welding of better accuracy. But in the case of LL0, the largest amount of deformation occurred because of (this) initial displacement. Moreover, it was practically difficult to fabricate FPDs of which the joint surfaces contacted each other with the butt joint. On the contrary, in the case of LL20, LL50, and LS, there was welding space between two joint surfaces. Therefore, they would not displace before laser welding. In LL20, LL50, and LS, only transverse contraction influenced the deformation of FPDs during laser welding.

The mesiodistal deformation of the FPDs in LL20, LL50, and LS groups tended to be larger than that in the buccolingual direction. This was because specimens were irradiated from the line angle of occlusal surface with a small laser energy assuming intraoral laser application. As a result, primary angular deformation occurred and the deformation could not be canceled by irradiation at a diagonal position (i.e., not able to irradiate directly below joint space). However, angular deformation by laser welding was smaller than 11-19 mrad (at final laser welding) as reported by Himi et al.\textsuperscript{2}, suggesting that FPDs could be made with the same level of geometric accuracy.

In addition, the deformation of FPDs after temporary welding also depended on the weld pool shape. In this study, the diameter of fusion zone in the weld pool shape was longer than the penetration depth, and this shape was common in low-power laser welding processes. In this study, there were no differences in weld pool shape among the groups. Therefore, weld pool shape did not affect welding deformation in this study.

On the other hand, teeth are not rooted directly in the alveolar bone. They are supported by periodontal ligament in the alveolar bone. Miura and Okada et al. reported that the displacement of natural teeth during clenching was 20-150 μm\textsuperscript{20,29}, while Morikawa reported that the displacement of implants was approximately 40 μm\textsuperscript{20}. Kasahara reported that there was interdental space between neighboring teeth in a resting condition, and that this space was closed when teeth were in function\textsuperscript{20}. Moreover, we fabricated the prostheses by an indirect technique. Therefore, some errors — such as those arising from thermal expansion of the investment and casting shrinkage of cast metal — were unavoidable in the manufacturing process. Due to these manufacturing-induced errors, long-span FPDs are fabricated by being divided into several units. After try-in, FPDs are fixed by soldering or laser welding. It became clear that temporary fixation by Nd:YAG laser would be very useful in maintaining an accurate positional relationship between retainers in the oral cavity. Moreover, increasing of welding gap leads to smaller welding strength and higher probability of porosity. Therefore, from this experiment, we recommend that 20-μm welding gap gives the least deformation for temporary fixation with laser welding.

Strength of FPDs after temporary welding:
Strength of FPDs after temporary fixation plays an important role in preventing deformation during final fixation. Therefore, temporary-fixed FPDs are usually reinforced with dental stone or investment before final fixation. In the same vein, we measured the deformation of temporary-fixed FPDs after investing. The FPDs were invested with a soldering investment and dissolved with a solution for dental stones (Supermelt, Shofu Inc., Kyoto, Japan). Deformation of the FPDs was then measured at the marginal ridge of each retainer as described in Materials and Methods. There were no significant differences in the readings before and after the investment procedure. This result suggested that the strength
of FPDs after temporary fixation was adequate for the laboratory procedure.

CONCLUSIONS

In this study, we examined the accuracy of temporary laser welding of FPDs by Nd:YAG laser which can be used in the oral cavity. The following conclusions were obtained:

1. It was possible to predict the deformation of FPDs by comparing the normal vectors of the marginal edge of retainers, whereby calculations were based on multipoint measurement.

2. Under a condition with no soldering space (LLD), large FPD deformation occurred because of primary displacement of retainers. In other words, a minimal amount of welding space was needed when laser welding was applied to the FPDs.

3. Welding gap of 20 μm resulted in the least angular deformation of FPDs after temporary welding.

REFERENCES