Analysis of Stress Distribution in a Screw-Retained Implant Prosthesis

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Four types of implant superstructures were screwed onto implant bodies, and the strains created around the implant bodies were compared and analyzed within the IMZ Implant System. Three IMZ implants were embedded in the center of a polyurethane block (30 × 40 × 30 mm), and a total of 16 superstructures was fabricated by 4 methods: 1-piece cast, 1-piece cast/split soldering, soldering, and passive fit. Six strain gauges were placed on the surface of the block 1 mm apart. Three embedded implants were numbered, and a fixed partial denture was placed on these implants and screwed by a torque wrench using 14.5 Ncm torque. This procedure was repeated 7 times for each fixed partial denture, and each created strain was measured when the last screw was tightened. In all fixed partial dentures, strains were produced around the implant bodies when screws retaining the prosthesis were tightened, and the strain was relieved with unscrewing. The magnitude of strain was greater with the 1-piece cast method or the section/solder method than with the soldering and passive-fit methods. Of the 2 soldering methods, when the screw on the middle implant was tightened before those on the terminal 2 implants, the magnitude of strain was lower with the soldering method than with the 1-piece cast/split soldering method. When the order of screw tightening was changed, there were significant differences in the magnitude of strain at each gauge with the soldering method. With the passive-fit method, no differences in the magnitude of strain attributable to the order of screw tightening could be detected. The magnitude of strain produced around a screw-retained implant prosthesis was significantly lower with the passive-fit method when compared to the other 3 fabricating methods. Furthermore, the implants prepared by the passive-fit method were not affected by the order of screw tightening. (Int J Oral Maxillofac Implants 2000;15:209–218)

Key words: *implant prosthesis, passive fit, strain gauge, stress distribution, tightening screw*

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Precise fit between an implant body and an abutment and between an implant abutment and a superstructure are important factors in determining the long-term success of implant-supported restorations. Thus, when these fits are poor, tensile, compressive, and bending forces may be introduced into an implant-supported restoration and may result in loosening of the prosthesis or abutment screws, distortion or breakage of the restoration, microfractures in the bone surrounding the implant, or fracture of the implant body. As a result, they may induce loss of osseointegration.[1–7]

To improve the fit between an implant abutment and its superstructure, various methods, such as impression collection,[8,9] soldering,[10] and casting,[11] have been developed. It has been difficult to fit long-arch superstructures snugly and passively against the abutments by casting alone (Fig 1).[12]

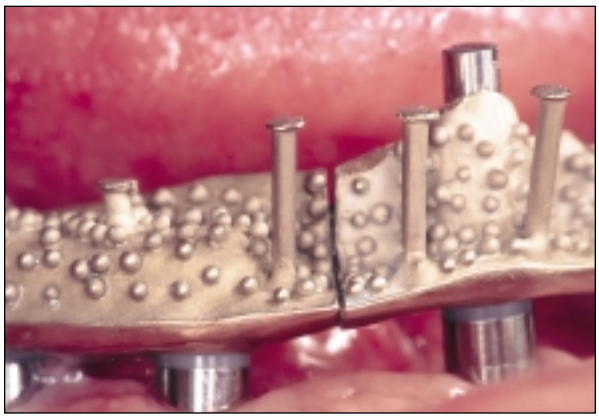

Fig 1 Discrepancy of framework at trial fit.

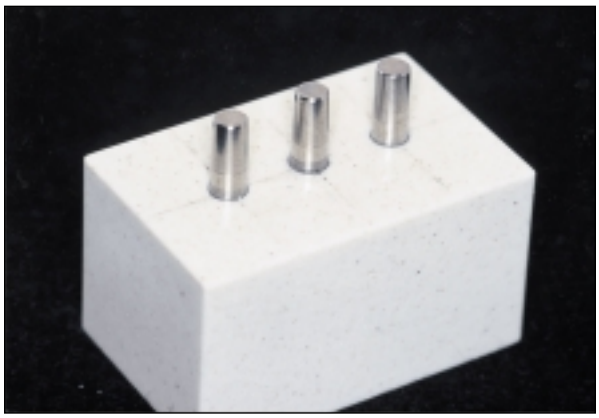

Fig 2 Experimental model.

Klineberg and Murray[12] proposed that 90% of the contact surface between an abutment and its superstructure should have a gap within the range of 30 µm. However, this gap would not be clinically detectable, and consequently a cast framework that seems upon visual examination to fit well could undergo distortion or deformation of the contacting surfaces during the tightening procedure. Riedy et al[13] measured the contact surface between an implant-supported fixed partial denture (FPD) and its abutments and analyzed the morphology of the abutment through the use of a 3-dimensional digitizer. They reported poor fit of contact surfaces produced by tightening screws between the implant-supported FPD and its abutments.

Patterson[14] defined the concept of passive fit as the state in which there is no gap between the bearing surface of a fastened superstructure and its abutments with no unfavorable strain. Based on this concept, several passive fit techniques have been developed to solve the misfit created by the casting process.[15–17] Neuendorff devised a method for achieving "passive fit" with the IMZ Implant System (Friadent, Mannheim, Germany) and applied it to the fabrication of implant-supported FPD.[18,19] This method utilizes specially made fastening screws, fastening sleeves, plastic sleeves, and titanium copings. After a superstructure is fabricated, titanium copings are anchored to implant bodies in the mouth using fastening screws, and the contact surfaces between the superstructure and the titanium copings are removed. The titanium copings and the superstructure are then joined by the use of adhesive resin.

Currently, at least 4 fabrication methods are available for clinical use: *(1)* the 1-piece cast method; *(2)* the sectioning and soldering method (a 1-piece cast superstructure is cut into pieces corresponding to each abutment, and the pieces are reassembled and soldered); *(3)* the soldering method (a superstructure is waxed for each abutment, each piece is cast, and then all are assembled by soldering); and *(4)* the IMZ "passive-fit" system.

The objective of this study was to investigate the strain produced around implants when superstructures fabricated by these 4 methods were screwed onto supporting implants, and also to investigate the strain produced when the order of screw tightening was changed.

MATERIALS AND METHODS

A 30 × 40 × 30 mm polyurethane block (Nisshin Dental Products Inc, Tokyo, Japan) was used as an implant receptor. Three holes, 13 mm in depth, were drilled in the middle of the block 10 mm apart and parallel to the long axis of the block. These receptor sites were prepared according to a protocol for clinical use using IMZ drills attached to a milling machine. IMZ Twin Plus cylindric implants (4 mm diameter, 13 mm length) were then placed into the receptor sites and anchored using cyanoacrylate adhesive (Fig 2).

IMZ Kinetic Line impression posts were attached to the implant bodies, and a silicone impression (Exaflex, GC Industrial, Tokyo, Japan) was made using a custom resin tray suitable for the test block. After the impression posts and the implant analogs were connected, they were returned to the impression, which was poured in stone (Suprastone, Kerr Corp, Romulus, MI) to make the working cast.

Sixteen implant-supported superstructures were fabricated on the working cast using 4 different methods. In the 1-piece casting method, waxing was

performed by the conventional method using plastic sleeves and fastening screws, and the completed wax pattern was left on the die for 12 hours at room temperature. It was then invested using vacuum-mixed cristobalite investment (GC Industrial) at the standard water powder ratio (0.33 w/p). The ring with invested pattern was placed in the oven at 200°C for 40 minutes; then the temperature was raised by 6°C per minute to 700°C. This temperature was maintained for 30 minutes. Type IV gold alloy (GC Industrial) was then used for casting. After careful removal of the investment, the casting was washed in amidosulfuric acid (Neacid, Degusta, Germany) for 5 minutes using an ultrasonic cleaner.

In the sectioned/soldering method, a 1-piece cast FPD frame was cut into 3 sections using a diamond disk. Soldering gaps were created using 250-μm-thick separating disks (Shofu, Kyoto, Japan). A titanium intramobile connector (IMC) was then screwed into the implant bodies on the polyurethane block, and the cast sections were anchored to the titanium IMC by fastening screws with a torque wrench (Friatec, Mannheim, Germany) using 14.5 N·cm torque. They were assembled using pattern resin (GC Industrial) and soldered.

In the soldering method, the prosthesis was waxed in 3 separate sections. They were invested and cast under the same conditions as the sectioned/soldering method. Soldering gaps were created using 50-μm-thick metal strips. In the above 2 methods, the soldering procedure was accomplished as follows. Each cast section was arranged and invested in the soldering block using a soldering investment (GC Soldering Investment, GC Industrial) and a pressure-investment machine (Yoshida, Tokyo, Japan). This block set for 1 hour under 6 atm and was preheated in a furnace for more than 30 minutes at 200°C. The temperature of the furnace was raised to 450°C and maintained for 30 minutes.

The "passive-fit" method was employed as reported by Neuendorff.[20] This method is illustrated in Figs 3a to 3j. The passive-fit method is a technique that attempts to compensate for the shrinkage or deformation produced by casting to fabricate a screw-retained prosthesis. A specific titanium coping, plastic sleeve, and fastening screw were used for the passive fit method (Altatex, Stuttgart, Germany) (Fig 3a). A conventional polymer sleeve was placed and secured on one of the terminal implant analogs in the working cast with a fastening screw (Fig 3b). On the other 2 implant analogs in the working cast, a titanium coping and plastic sleeve were placed and secured with fastening screws (Fig 3c). Waxing was carried out in the same way as in the conventional method of the IMZ Implant System (Fig 3d). The wax pattern was removed from the working cast and the titanium coping was removed, invested, and cast. After casting, the inner stopper of the casting corresponding to a polymer sleeve in the prosthesis was removed using a carbide bur (Fig 3e). Titanium copings were then anchored to the implant by a titanium fastening screw and the surface of the copings was coated by green rouge dissolved in chloroform (Fig 3f).

Castings were placed on the working cast and on the contact spots between their internal surfaces, and the titanium copings were verified and removed using a round carbide bur (Fig 3g). The outer surface of the titanium copings was sandblasted with 50-μm aluminum oxide and the copings were replaced on the implants in the working cast. The heads of fastening screws were relieved by wax (Fig 3h). The FPD and copings were then attached using adhesive resin cement (Super Bond C & B, Sunmedical Co, Shiga, Japan) (Figs 3i and 3j).

Six strain gauges were placed on the surface of the polyurethane block, 1 mm apart from the implant bodies (Fig 4). They were designated G1 through G6, as shown in Fig 5. Strain gauges G1 through G4 were placed in line with the implants, and G5 and G6 were placed next to the central implant perpendicular to the straight line of the implants. Data from the 6 gauges were transferred to the strain amplifier (AS1203 High-Performance Model, NEC SANEI, Tokyo, Japan) and analyzed by the Mac Lab.

In this study, 2 experiments were performed. In Experiment 1, the effect of the order of screw tightening on the FPD fabricated using the passive-fit and soldering methods was investigated. The sequences used for screw tightening were: $1 \rightarrow 2 \rightarrow 3$, $1 \rightarrow 3 \rightarrow 2$, and $2 \rightarrow 1 \rightarrow 3$ (2 denoting the central implant and 1 and 3 denoting the terminal implants). The screws were tightened and secured with a torque wrench using 14.5 N·cm torque. Fastening of the FPD with screws was repeated 7 times for each FPD to minimize measurement error. The strain produced by each screwing sequence was measured as the last screw was tightened. One-way analysis of variance (ANOVA) was applied individually on the 2 fabrication methods in Experiment 1.

In Experiment 2, the magnitude of strain at each gauge was compared and analyzed among the 4 FPD fabrication methods. Strain measurements were repeated 7 times using the screwing sequence $2 \rightarrow 1 \rightarrow 3$, which would be commonly used in the clinic.

Two-way ANOVA with split plot design was applied to analyze differences in the magnitude of strain attributable to the location of strain gauges and the fabrication method.

Figs 3a to 3j Series showing the passive-fit method of the IMZ Twin Plus System.

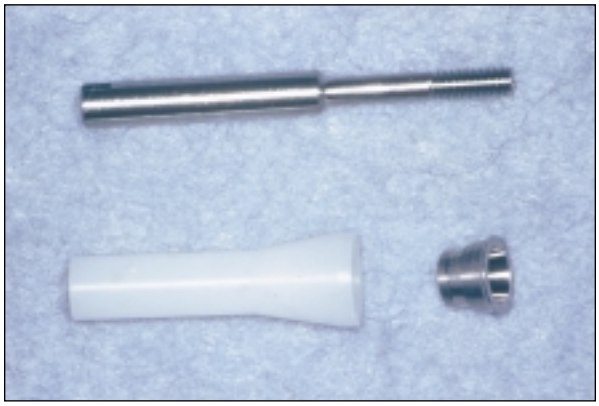

Fig 3a Titanium coping, plastic sleeve, and fastening screw for the passive-fit method.

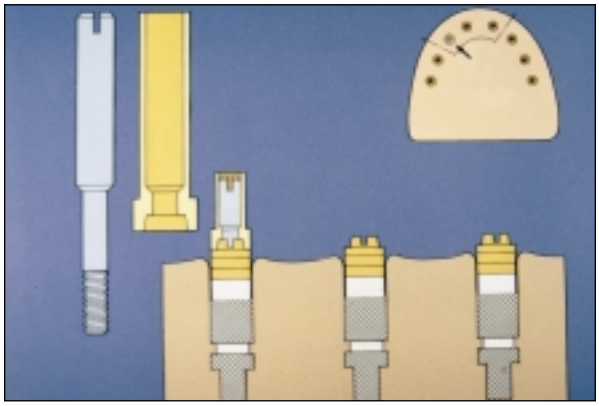

Fig 3b A conventional polymer sleeve is placed and secured with a fastening screw on one of the terminal implant analogs in the working cast.

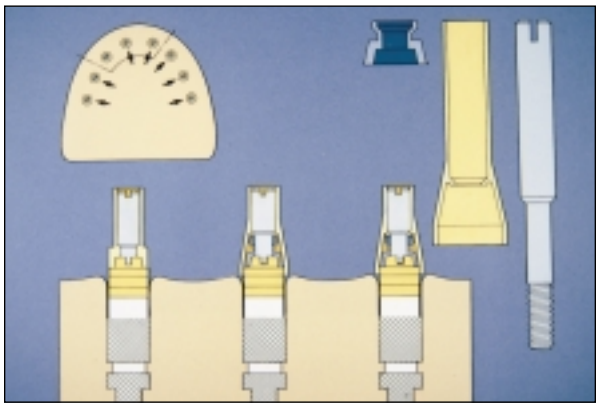

Fig 3c Titanium copings and plastic sleeves are placed and secured with fastening screws on the other 2 implant analogs on the working cast.

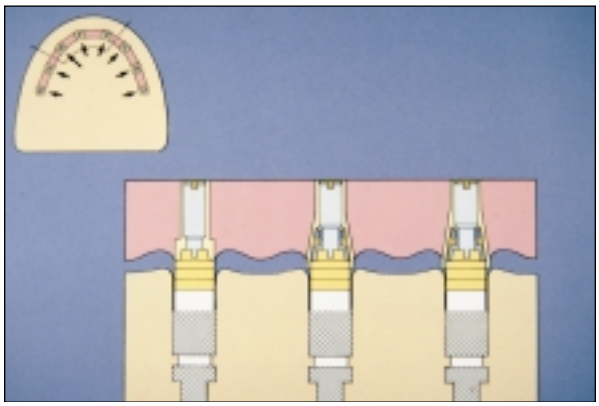

Fig 3d Waxing is carried out in the same way as in the conventional method.

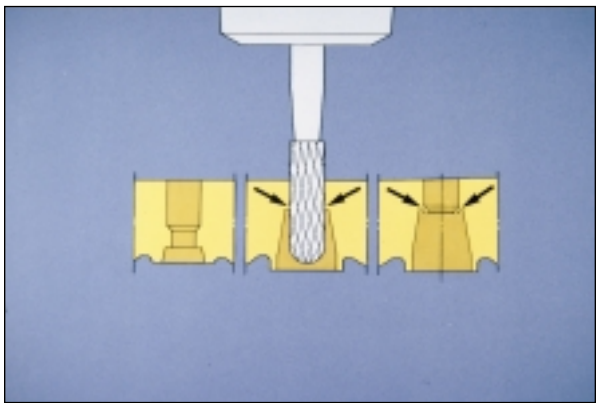

Fig 3e After casting, the inner stopper of the casting corresponding to a polymer sleeve in the prosthesis is removed with a carbide bur.

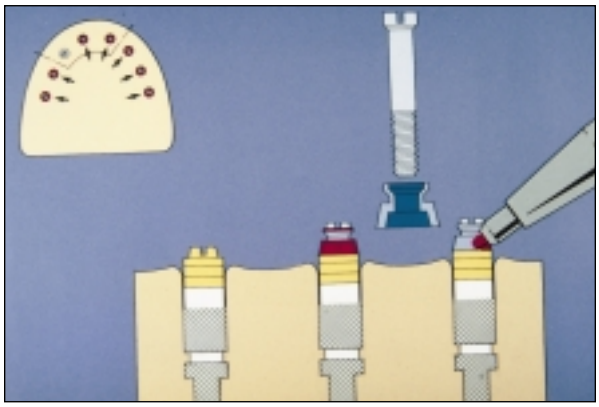

Fig 3f The titanium coping is then anchored to the implant by a titanium fastening screw, and the surfaces of the copings are coated by green rouge.

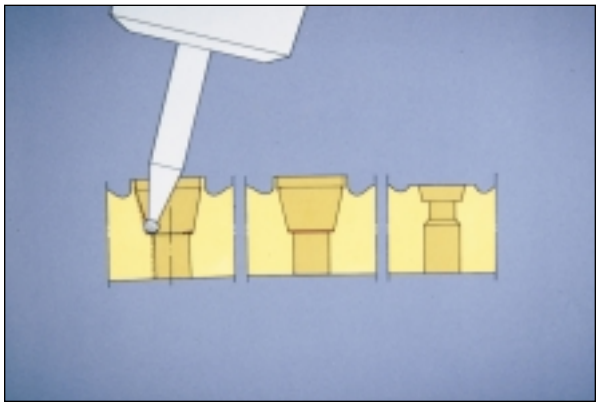

Fig 3g Castings are placed on the working cast and the contact spots between the internal surface within them, and the titanium copings are checked and removed using a round carbide bur.

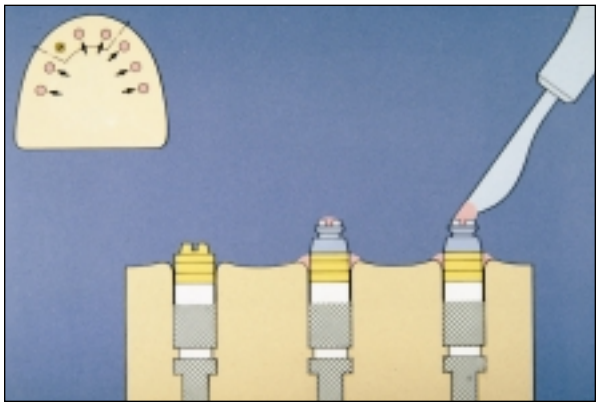

Fig 3h The titanium copings are placed on the implants in the working cast and the heads of the fastening screws are relieved by wax.

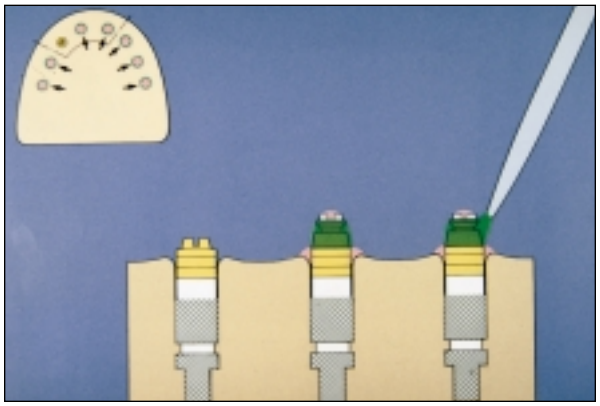

Fig 3i The copings are then attached using adhesive resin cement.

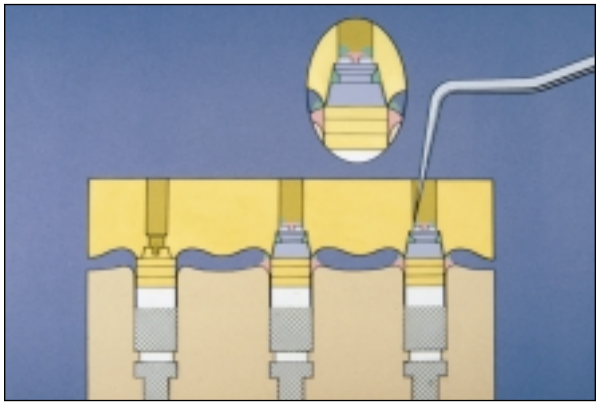

Fig 3j Surplus adhesive resin cement is removed with an explorer.

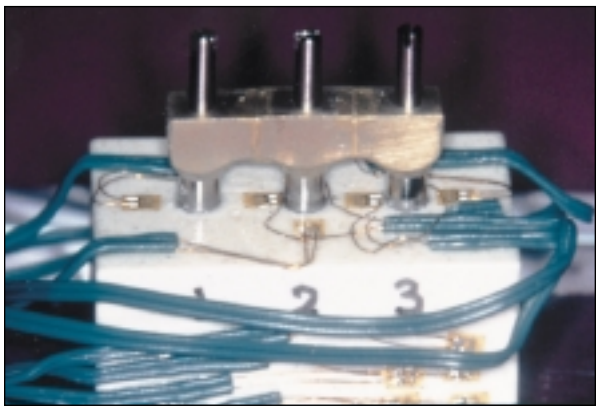

Fig 4 Experimental master model with strain gauges attached.

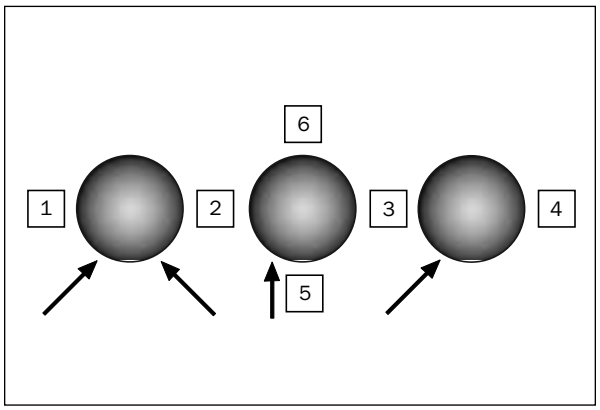

Fig 5 Experimental master model showing number and orientation of strain gauges. *Arrows* = implant bodies; numbers indicate strain gauges.

Table 1 Data from Experiment 1

	Amount of strain (με)						
Screwing order	G1	G2	G3	G4	G5	G6	Mean
Passive fit							
1-2-3	188	201	111	57	25	130	119
1-3-2	188	197	94	54	5	119	110
2-1-3	52	53	85	25	65	22	50
Soldering							
1-2-3	358	878	296	113	249	187	347
1-3-2	317	641	262	84	118	120	267
2-1-3	119	166	354	107	70	32	141

RESULTS

For all implant-supported FPD fabrication methods, strain was produced during screw tightening, but it disappeared when the screws were loosened.

Experiment 1

The experimental results shown are the average values of 7 measurements (Table 1). These were analyzed by 1-way ANOVA. Figures 6a and 6b show these results. With the passive-fit method, the order of screw tightening had little effect on the amount of strain measured by the 6 gauges (G1 to G6) (Fig 6a). The FPDs fabricated by the soldering method showed differences in strain values despite the use of the same gauges and order of screw tightening (Fig 6b). The magnitude of strain differed among the 6 strain gauges. In both fabrication methods (passive fit or partial soldering), the strain for screwing order $2 \rightarrow 1 \rightarrow 3$ was lower than with orders $1 \rightarrow 2 \rightarrow 3$ or $1 \rightarrow 3 \rightarrow 2$. These tendencies were especially remarkable at gauges 1 and 2 (G1 and G2).

Experiment 2

Table 2 shows the experimental results by an average value of the 7 measurements for each fabrication method. Differences in the magnitude of strain attributable to the location of strain gauges and the fabrication methods were analyzed by 2-way ANOVA with split plot design, and these results are shown in Table 3 and Fig 7. Significant differences ($P < .05$) were found among the 4 superstructure fabrication methods. The passive-fit method showed a strain of 50 με, the soldering method 154 με, the 1-piece casting 366 με, and the 1-piece cast split/soldering method 737 με. Furthermore, strain patterns among the 6 strain gauges were different. The average strain value was calculated as the absolute value.

DISCUSSION

In all of the test specimens, strains produced by fastening screws were completely relieved when the screws were loosened.

Experiment 1

With the passive-fit method, the amount of strain was low and the order of screw tightening was not statistically significant. The magnitude of strain on the superstructure made by the soldering method was strongly affected by the screwing order, and it differed among the 6 strain gauges. This was thought to be caused by the poor fit between the internal surface of the FPD and the titanium IMC on the implant body. When the FPD was fabricated precisely, the magnitude of strain was not affected by the screwing order; but with an imprecise fit, it was affected by the screwing order. The magnitude of strain for screwing order $2 \rightarrow 1 \rightarrow 3$ was lower than for $1 \rightarrow 2 \rightarrow 3$ or $1 \rightarrow 3 \rightarrow 2$. It seems that by first tightening the middle implant, strain could be diffused and tensile forces would be exerted on the terminal implants. The magnitude of strain was shown by higher values at G1 and G2. A comparison between soldering and the passive-fit method showed higher values for the former at these 2 gauges. In an FPD fabricated with the passive-fit method, a titanium coping was placed on the implant bodies before the internal surface of the FPD was attached to the copings. As a result, an FPD was precisely positioned, and decreased strain value was obtained.

Experiment 2

As shown in Fig 7, the average magnitude of strain measured by the 6 gauges differed among the 4 FPD fabrication methods. The magnitude of strain produced by screwing was relatively low on the FPDs

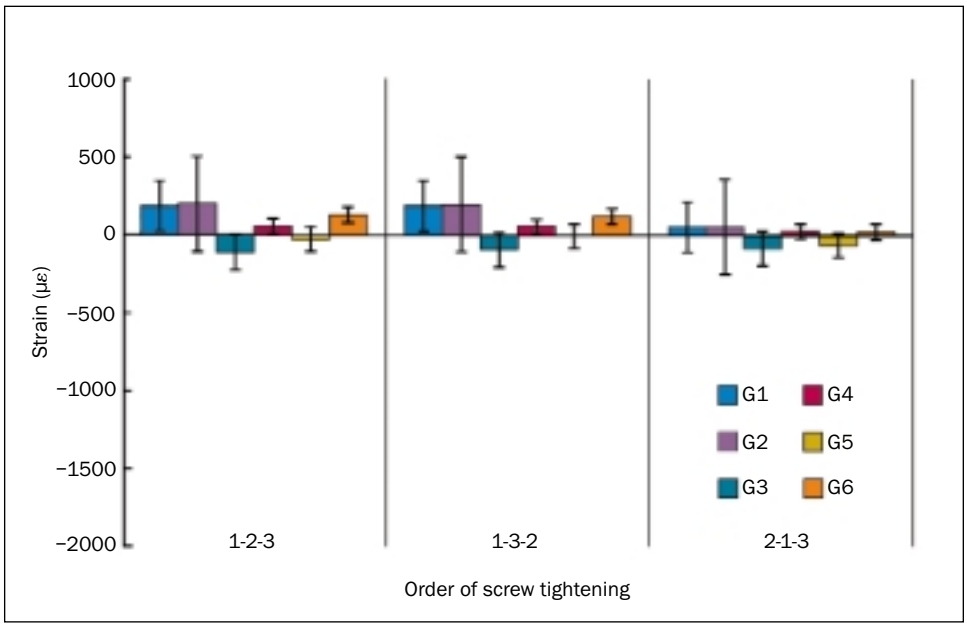

Fig 6a Graph showing the effect of changing the order of screw tightening in FPDs fabricated with the passive-fit method. Lines indicate 95% confidence interval.

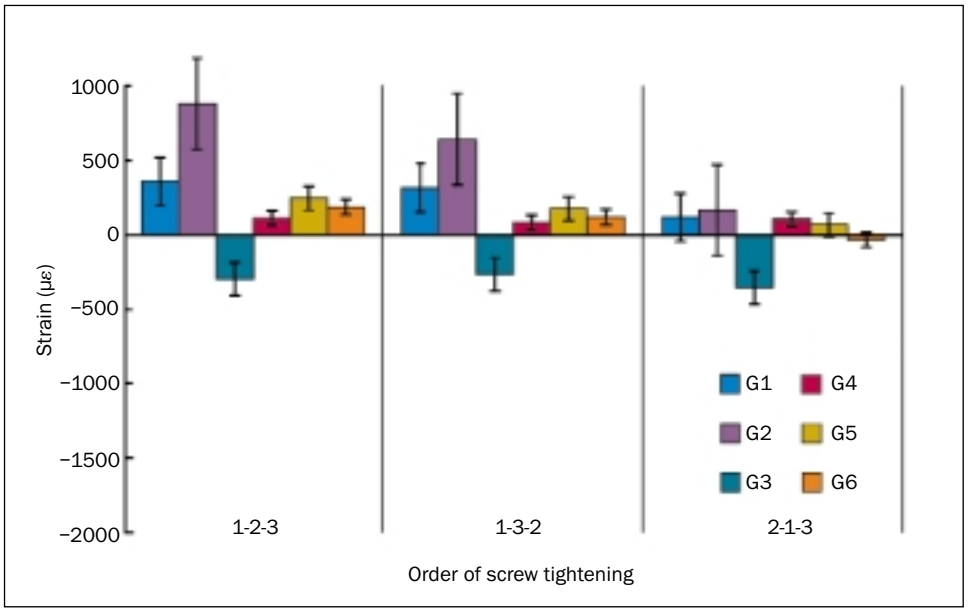

Fig 6b Graph showing the effect of changing the order of screw tightening in FPDs fabricated by partial soldering. Lines indicate 95% confidence interval.

Table 2 Data from Experiment 2

	Amount of strain (με)						
Fabrication method	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**Mean**
One-piece cast	50	53	85	25	65	22	50
One-piece cast and split-soldered	3	1391	10	205	164	42	366
Soldered	842	177	1747	594	690	370	737
Passive fit	119	166	354	107	70	32	154

fabricated using the passive-fit or soldering methods, while it was higher for the FPDs fabricated by the 1-piece cast or 1-piece split/soldering methods. This difference is thought to be the result of the degree of fit between the internal surface of the FPD and the titanium IMC on the implant. Therefore, when an FPD is fabricated by either the 1-piece cast or the sectioned and soldering method, the fit between the FPD and IMC is compromised by such factors as pattern deformation or cast shrinkage.

When the soldering method was used, the degree of deformation by cast shrinkage was lower when compared with the 1-piece cast method, because each FPD piece was fabricated separately and connected by soldering. There was a significant difference between the 1-piece cast method and the section/solder method in the magnitude of strain measured at the same gauge. This may be the result of poor fit between the FPD and the IMC, or of deformation of the FPD. In the case of a long-span implant-supported restoration fabricated by the 1-piece cast method, the superstructure should be cut into several pieces and soldered. The results of this study show that even if the fit is visually determined to be favorable, strains are produced around an implant when the FPD is screwed into place. As specified by White,[21] while visually confirmed fit is important, it is more important that the fit between implant bodies and their superstructure does not cause strain around the implant.

Today, from a scientific point of view, the acceptable range of this fit has not been determined. It is thought that the acceptable range of fit for screwing an FPD onto an implant abutment differs from that of the fit of crowns on abutment teeth. The natural tooth can move up to 100 μm within its periodontal ligament; thus a certain degree of misfit of an FPD is compensated, whereas an osseointegrated implant has limited movement, in the range of 10 μm within bone elasticity.[22] Under these conditions, as the gap of approximately 30 to 100 μm with crowns or FPDs is filled with cement, injurious strain is usually not produced. But a 30-μm gap for screwing an implant FPD into place will likely produce a high degree of strain around the implant bodies.

Table 3 Statistical Analysis by 2-way ANOVA (Experiment 2)

Factor	Sum of squares	Degrees of freedom	Mean square	F value
R	1.82	3	0.61	1.83
A	7.62	3	2.54	7.70*
e1	2.97	9	0.33	0.51
B	66.92	5	13.38	20.75†
A × B	135.19	15	9.01	14.00†
e2	38.70	60	0.64	
Total	253.21	95		

*Significant ($P < .05$); †Highly significant ($P < .01$).
A = fabrication method; B = position of strain gauge.

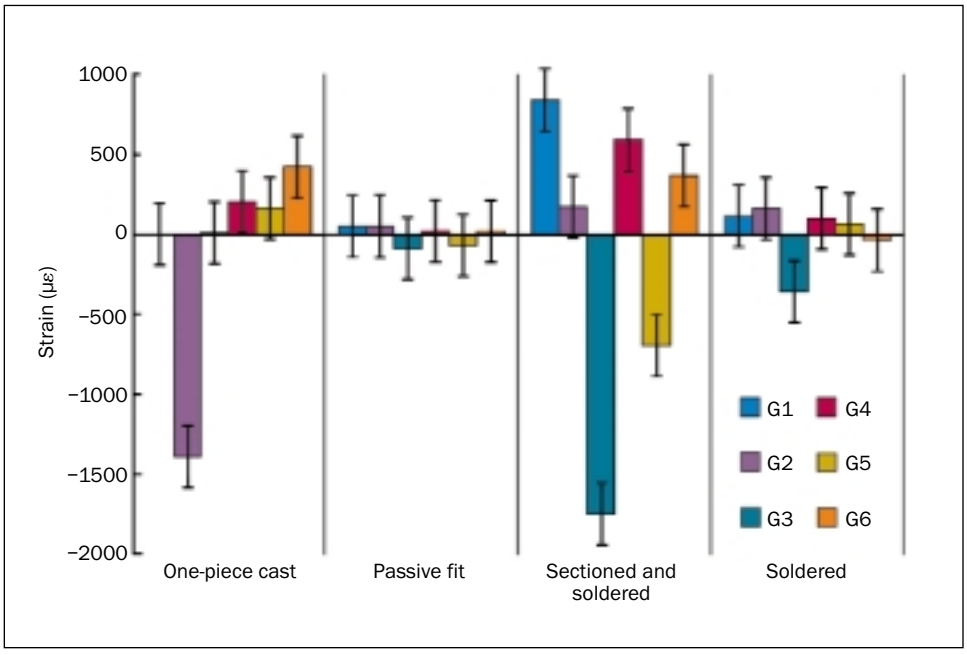

Fig 7 Graph showing the effect of the difference in fabrication methods. Lines indicate 95% confidence interval.

Millington and Leung[23] conducted a preliminary study using photoelastic models and found that when there was a 6-μm gap between an abutment and its superstructure, strains were created on the surface of the superstructure. In addition, Brunski[24] suggested in his in vitro study that if compressive force was applied to a superstructure, the strain patterns that appeared on each implant were uneven. Carr et al[25] measured the bone response around implants placed in the mandibles of baboons that supported prostheses exhibiting 2 levels of fit and that were not loaded occlusally. Screw-retained prostheses that exhibited a mean linear distortion of 38 μm and 345 μm made up the fit and misfit groups, respectively. They reported that the tensile surface analysis revealed that the percentage of fit (52.2%) and misfit (57.4%) integration was not substantially different (*t* test, $P > .05$). No mention was made of how the degree of misfit would affect bone resorption around the implant, because the study had a small sample size and did not measure interface strain.

Majzoub et al[26] evaluated the effect of early orthodontic loading on the stability and bone-implant interface of titanium implants in a rabbit model. As a result, no differences could be found between the pressure and tension surfaces of the test implants relative to bone quality and density within a range of 1,000 μm from the implant surface.

Jemt and Book[27] investigated the statistical correlation of in vivo measurements of screw-retained prosthesis misfit and change of marginal bone level in implants placed in the edentulous maxilla. The mean center point misfit was 111 μm for the 1-year group and 91 μm for the 5-year group. The authors indicated that no statistical correlation ($P > .05$) could be ascertained between observed marginal bone level changes and different parameters of prosthesis misfit. These results do not point out the relationship between difference of fit and bone resorption because these implants were connected and the sample size was too small.

Brånemark has stated that well-controlled load is necessary for stimulation of bone remodeling and maintenance of osseointegration.[28] This concept is based on Wolff's law, which describes remodeling of bone as a response to the functional demands placed upon it, so that it would have strength where it is needed.[29] Frost[30] also stated the principle in terms of bone metabolic units, which are the building blocks of a special kind of lifelong turnover or renewal of lamellar bone tissue. Unfortunately, the quantitative effect of stress upon the remodeling process is poorly defined.

The present study addressed statistical stress analysis when fastening screws were tightened to seat fixed partial prostheses fabricated by different methods. The strain during dynamic loading was not measured. A subsequent study could investigate dynamic loading involving occlusion and its effect on bone resorption with different degrees of misfit. With respect to the above-mentioned reports, the range of misfit used in this study might not cause loss of osseointegration. However, such misfit might cause loosening of fastening screws, fracture of implant parts and superstructures, and, secondarily, loss of osseointegration.

In daily clinical applications, an FPD that has visually detectable gaps or rocking movement on abutments would not be placed. Nonetheless, after an apparently well-fitting FPD is fastened to implant bodies, it may become necessary to refasten screws several times relatively soon after the restoration is placed in function (within 1 year) in some patients. These clinical findings suggest that even though the fit between a superstructure and an implant is visually confirmed, tensile forces can be applied to implant bodies when the abutment and internal surface of the FPD are forcibly fitted, thus producing strain around the implant bodies.

CONCLUSION

The magnitude of strain produced in the bone around implants supporting screw-retained implant superstructures was investigated with respect to FPD fabrication methods and the order of screw tightening during seating. The following conclusions were drawn:

1. Regardless of the type of implant FPD utilized, strains were produced around the implant bodies when an FPD was screwed into place, and they disappeared when it was unscrewed.
2. The magnitude of strain differed at each strain gauge, regardless of the FPD fabrication method.
3. The magnitude of strain was greater with the 1-piece cast method and the section/solder method than with the soldering method alone.
4. With respect to the 2 soldering methods, when screws were tightened in the order of center screw first, then the 2 terminal screws, the magnitude of strain was lower with the soldering method than with the section/solder method.
5. The order of screw tightening affected the magnitude of strain at the 6 gauges when FPDs fabricated by the soldering method were fastened, but it did not remarkably affect strain in FPDs fabricated by the passive-fit method.

6. With the passive-fit method, there were no significant differences in the magnitude of strain measured at the 6 gauges when the tightening order was changed.

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