Fixation of 5-Unit Implant-Supported Fixed Partial Dentures and Resulting Bone Loading: A Finite Element Assessment Based on In Vivo Strain Measurements

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Purpose: *It is believed that implant-supported fixed partial dentures (FPDs) should display passive fit. The objective of this in vivo–based finite element analysis (FEA) was to quantify the magnitude of bone loading occurring on account of the fixation of cemented or screw-retained 5-unit superstructures.* ***Materials and Methods:*** *Based on a patient situation with 3 implants, 4 different groups of restorations with 10 samples each were fabricated. Strain gauges on the pontics of the restorations were used for in vivo measurements. Using the values obtained, bone loading in 3-dimensional FE models was simulated as von Mises equivalent stress.* ***Results:*** *The in vivo measured mean strain values ranged from 32 µm/m to 458 µm/m at the different sites. FEA revealed stresses between 5 and 30 MPa in the cortical area, while in trabecular bone values ranging from 2 MPa to 5 MPa were observed. Stress of a similar magnitude was found for axial implant loading with 200 N.* ***Discussion:*** *Assuming that the axial loading of a single implant with 200 N is within the realm of the bone's adaptation ability, it would appear that the amount of stress resulting from the fixation of superstructures alone does not constitute a risk.* ***Conclusions:*** *The level of precision of fit which can be obtained in superstructure fabrication would appear to suffice to produce restorations that do not cause bone damage.* INT J ORAL MAXILLOFAC IMPLANTS 2006;21:756–762

Key words: *bone loading, cement fixation, finite element analysis, in vivo strain measurements, passive fit, screw retention*

The clinical and laboratory procedures used in framework fabrication are incapable of providing an absolute passive fit for fixed, implant-supported superstructures.[1,2] Several authors have addressed this issue as well as the possible implications of superstructures without passive fit.[3–9] The term "passive fit" itself, however, has never been defined in biomechanical terms.[10] According to Kan and colleagues,[11] no clinical techniques of measuring passive fit exist yet. In basic research studies dealing with strain development in implant-supported restorations,[12–15] the level of static implant loading caused by the fixation of various restorations has been quantified, and different procedures that could influence superstructure fit, such as impression making and laboratory procedures, have been investigated. Furthermore, the effects of static implant loading on osseointegration are still poorly understood.[16,17] While Melsen and associates[18] state that excessive loading may contribute as an etiological factor to the pathogenesis of failing implants, Jemt and colleagues[19] found that misfit stress levels of clinical magnitudes do not seem to jeopardize osseointegration per se, but seem to significantly enhance bone remodeling. Finite element analysis (FEA) lends itself well to the investigation of

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such matters, as it offers a deeper insight into the effects of implant loading and subsequent bone response.[20–22] The aim of this study was to quantify static implant loading generated by cemented and screw-retained implant-supported 5-unit fixed partial dentures (FPDs) using the strain gauge (SG) technique in vitro and in vivo. To illustrate the resulting stress in the bone around the implants caused by superstructure fixation, an FEA was conducted.

MATERIALS AND METHODS

At the outset of the study,[13] the strain development of screw- and cement-retained 5-unit implant-supported FPDs was investigated in vitro. As the measurement model used for the in vitro tests and thus the prostheses examined had been fabricated on the basis of the oral situation of a volunteer patient, identical FPDs could be fixed on the implants in the patient's mouth for strain measurements in the in vivo study.

In Vitro Testing

A measurement model (SG-Am, SG-Ad, SG-Bm, SG-Bd, SG-Cm, SG-Cd) with implants A, B, and C from mesial to distal (solid screw implants, 4.1 mm in diameter, 12 mm bone sink depth; Straumann, Waldenburg, Switzerland) was fabricated according to an existing patient situation and equipped with strain gauges (LY11-0.6/120; Hottinger Baldwin Messtechnik, Darmstadt, Germany). The model was utilized for in vitro strain measurements on the pontics (SG-pAB, SG-pBC) of the FPDs and on the bone surrogate[23] (epoxy resin [Araldit]; Ciba-Geigy, Wehr, Germany) around the implants (Fig 1). By means of a special software (BEAM version 3, AMS, Flöha, Germany), it was possible to record the strain values as they were evoked through the fixation of the different superstructures.

Four groups of 5-unit FPDs were made using standard methods of superstructure fabrication. The entire procedure, including impression making, master cast fabrication, waxup, casting, and finishing, was carried out in accordance with recommended protocols.[12,13] Table 1 lists the 4 FPD groups (each containing 10 samples) which were fixed on the implants using cement fixation (ImProv; Nobel Biocare, Göteborg, Sweden) and screw retention (Straumann SCS fixation screws with a torque of 20 Ncm[24] applied with an electric torque control instrument [Nobel Biocare]). The resultant strain gauge signals were recorded, and the absolute values of the final strain levels were used to calculate mean values for each strain gauge. In order to compare the different FPD groups with one another in terms of strain development, multivariate 2-sample tests were performed at a level of significance of $\alpha = 0.1$.

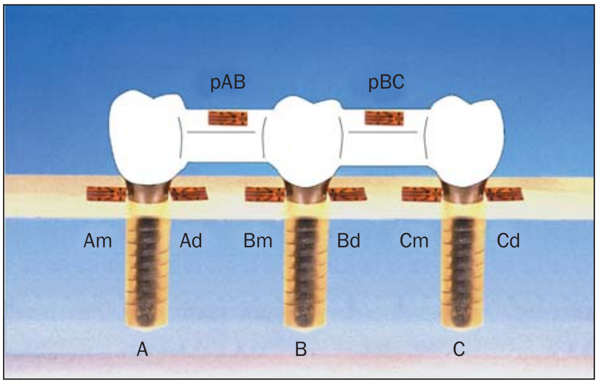

Fig 1 Illustration of the measurement model with implants A, B, and C fixed in epoxy resin (Araldit; Young's modulus 3 GPa) using autopolymerizing acrylic resin (Paladur; Heraeus-Kulzer, Hanau, Germany). Strain gauges were mounted mesially and distally adjacent to the implants (SG-Am, SG-Ad, SG-Bm, SG-Bd, SG-Cm, SG-Cd) and on the pontics (SG-pAB, SG-pBC).

In Vivo Testing

Informed patient consent and approval from the ethics commission (application no. 2315, Medical Faculty of the University of Erlangen) was obtained for all in vivo experiments. For ethical reasons, the FPDs (5 per group) which, according to the results of the in vitro tests,[13] best reflected the average strain development for their type were chosen for the in vivo investigation. In the oral cavity, the only strains measured were those that occurred at the pontics (SG-pAB, SG-pBC). The measurement equipment, the devices for fixation, and the strain gauges on the pontics used in vivo were identical to those used for the in vitro tests.[13] As was the case in the in vitro tests, the absolute values of the final strain levels were recorded for evaluation.

For the cemented restorations, a provisional cement (ImProv) was used. To reduce the cement strength, 2 aliquot of cement were combined with 1 of petroleum jelly. Spacers were luted onto the occlusal surface of the cementable FPDs between the strain gauges, and a brass bar was connected to them to allow the regular cementation protocol utilizing cotton rolls to be applied without damaging the sensors. Once the FPDs had been positioned on the abutments intraorally, the patient applied maximum bite force for 10 seconds and gradually reduced this force to a level which he was able to sustain for 3 minutes. After a total of 4 minutes, the patient was asked to release the force exerted on the FPD, and the cement was left to set for a further 2 minutes (Fig 2). The measurement period lasted for a total of 6 minutes.

Table 1 Abbreviations for the FPD Groups			
	FPD characteristics		
Abbreviation	Retention	Impression technique	Fabrication method
c-rep	Cemented	Repositioning	Plastic burn-out copings
s-pla	Screw-retained	Pickup	Plastic burn-out copings
s-cas	Screw-retained	Pickup	Cast to gold cylinders
s-bon	Screw-retained	Pickup	Bonded to gold

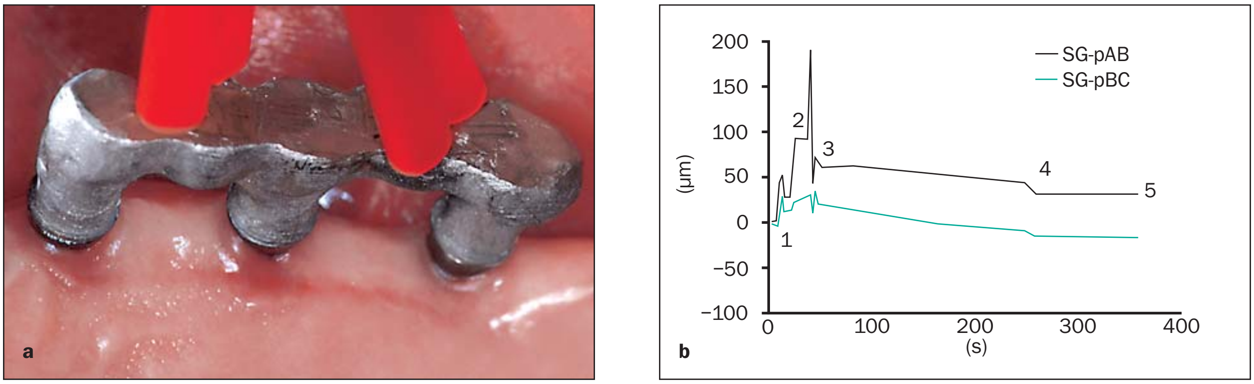

Fig 2 In vivo measurement of cementable FPDs. *(a)* FPD with strain gauges fixed on the pontics (SG-pAB and SG-pBC) placed on the abutments. *(b)* Strain gauge signals from SG-pAB and SG-pBC during the cementation procedure at different time points: *(1)* SGs set to zero; *(2)* maximum bite force applied; *(3)* force reduced and sustained for 3 minutes; *(4)* FPD relieved; and *(5)* final strain values recorded for analysis.

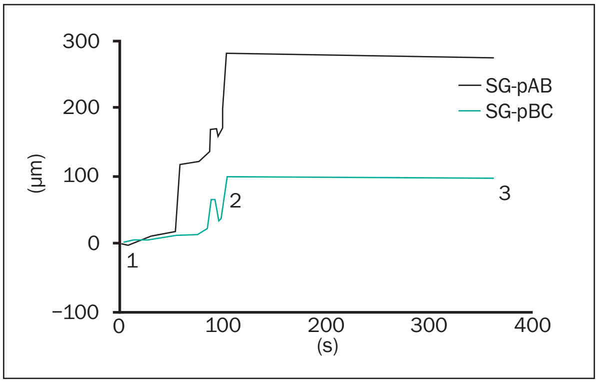

Fig 3 In vivo measurement of screw-retained FPDs. Strain-gauge signals from pontic strain gauges (SG-pAB and SG-pBC) during screw fixation at various time points: *(1)* SGs set to zero; *(2)* FPD placed on implants and fixation screws tightened; and *(3)* final strain values recorded for analysis.

The screw-retained FPDs were tightened on the synOcta abutments with a torque of 20 Ncm[24] using the electric torque control instrument. The fixation screws were tightened in a specific sequence (B, C, A). New fixation screws were used for each FPD. For reasons of comparability, the total measurement period was 6 minutes for both screw-retained and cemented FPDs (Fig 3).

FEA

To illustrate the stress levels in the peri-implant bone caused by the fixation procedures, a force calibration model and a bone loading model were generated using an FE program (MSC.Nastran; MSC Software Partner Solutions, Marburg, Germany). Bone was considered an isotropic material, and direct contact between the implant and bone was modeled with no relative motion possible at the interface. Hexa volume elements were used to model bone, the implant, and the FPD as elastic bodies (Young's modulus for the FPD frame, 160 GPa; for the implant, 100 GPa; for cortical bone, 17 GPa; for trabecular bone, 3 GPa; Poisson's ratio: 0.3).

As it is not possible to use µm/m values in an FE model which is calibrated for von Mises equivalent stress, an additional model, the calibration model, had to be designed. This model is calibrated for µm/m and represents the link between in vivo investigation and FEA. It allows the in vivo measured strain gauge values to be "translated" into corresponding vertical forces. These forces can be applied in the bone loading model, which is calibrated for von Mises equivalent stress, thus allowing the indirect simulation of the translated strain gauge values.

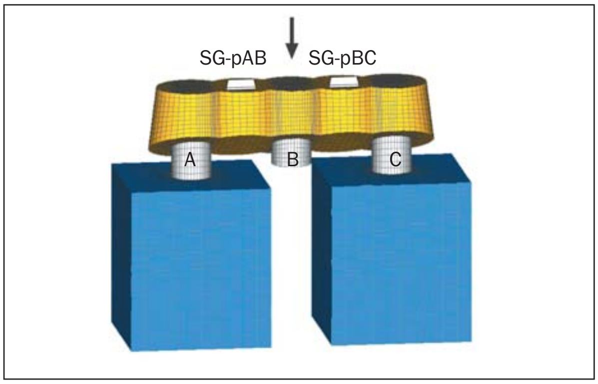

Fig 4 Illustration of the force calibration model, a 3-dimensional FE model used to analyze static implant loading. Implant B is separated and can be loaded with a vertical force *(arrow)*. This results in an inner preload which simulates the pontic strain values measured in vivo. The model displays strains in µm/m.

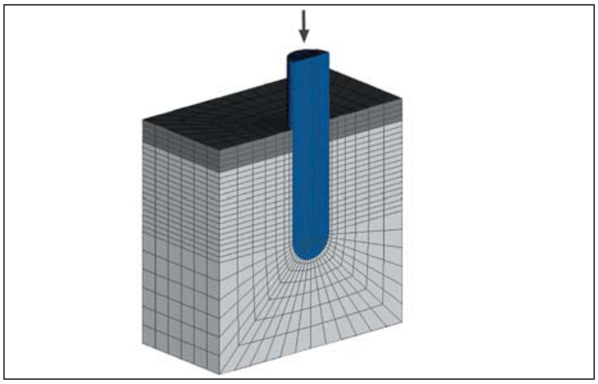

Fig 5 Illustration of the bone loading model, an FE model with higher stress resolution to simulate the stress situation in the bone surrounding implants A and C, respectively. The model is calibrated for von Mises equivalent stress.

Force Calibration Model

This model was calibrated for microstrains. The model margins were fixed on the 4 sides and at the bottom (Fig 4). The central implant B was separated, thus allowing the introduction of an inner preload into the FPD through the application of a vertical force. By altering the magnitudes of the force on implant B, the strain values of the pontic SGs (SG-pAB, SG-pBC; Fig 1) could be adjusted. In each case the higher measurement value of the 2 in vivo pontic SG values for each FPD group was chosen for FE simulation.

Bone Loading Model

As the force calibration model does not illustrate the specific stress situation in the bone around the implants, a refined FE model with the same material parameters was generated in order to illustrate higher stress resolution (Fig 5). The model showed the von Mises equivalent stress.[8,22,25] As the vertical force applied to implant B caused identical axial loading at implants A and C due to the rigidity of the FPD (Table 2), the model was reduced to 1 implant (Fig 4). To calculate the stress magnitudes in the bone around the implant, the loading magnitudes at the supporting implants measured with the force calibration model (Table 3) were used in the bone loading model (Fig 5). This model was also used for a comparison of the static loading situations evoked through FPD fixation with a single implant situation loaded under an axial force of 200 N.

RESULTS

In Vitro Strain Measurements

The mean values and standard deviations of the strain development for the FPD types investigated were published in a previous paper.[13] These values served as a basis for statistical comparisons between the involved sample groups. To provide sufficient background information for the interpretation of the in vivo and FE results presented, as well as for reasons of continuity, this part of the investigation was mentioned.

In Vivo Strain Measurements

The mean values and standard deviations of the strain levels at the FPD pontics (SG-pAB and SG-pBC) measured in vivo are shown in Table 2.

FEA

FEA was conducted on the basis of the mean in vivo strain gauge values of the c-rep, s-cas, and s-bon groups. The s-pla group was not selected for FE simulation because in the in vitro investigation[13] not significant difference ($P = .96$) from the s-cas group, which represents a more elaborate method of superstructure fabrication could be detected.[26] The different values for the vertical force, which were applied on implant B in the force calibration model to simulate the strain values measured in vivo, and the resulting vertical loads at supporting implants A and C, are given in Table 3. These values were subsequently used in the bone loading model.

Table 2 In Vivo Mean Final Strain Values in µm/m for the 4 FPD Groups with Standard Deviations

	SG-pAB		SG-pBC	
FPD group	Mean (µm/m)	SD	Mean (µm/m)	SD
c-rep	33	15	89	173
s-pla	302	83	197	139
s-cas	459	259	268	131
s-bon	270	65	53	53

Table 3 In Vivo Mean Strain Values and Corresponding Vertical Forces as Calculated in the Calibration Model and Applied to the Bone Loading Model

FPD group	Strain	Vertical force applied to implant B (N)	Resulting vertical load on implants A and C (N)
c-rep	89	178	89
s-cas	458	916	458
s-bon	269	538	269

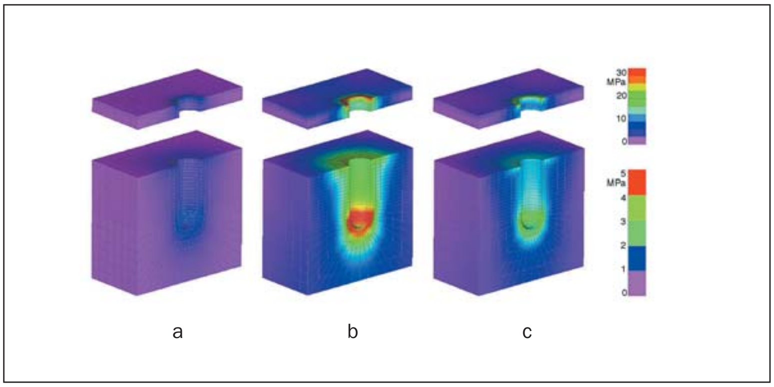

Fig 6 Von Mises equivalent stress in the bone surrounding the implant for *(a)* the c-rep group, *(b)* the s-cas group, and *(c)* the s-bon group. Note the different scales for cortical layer and trabecular bone.

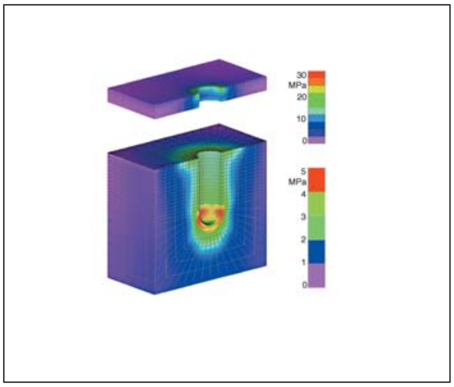

Fig 7 Von Mises equivalent stress resulting from 200-N axial loading.

The FE images with the von Mises equivalent stress values caused by in vivo cement and screw fixation of the 3 FPD types and simulated in the bone loading model are illustrated in Fig 6. The greatest stress occurred in the screw-retained FPDs cast to gold cylinders (s-cas), with as much as 30 MPa in the cortical layer and more than 5 MPa in the apical area of the trabecular bone (Fig 6b). Symmetrical stress distribution of 3 to 4 MPa can be seen at the lateral aspect of the implant. Far lower stresses were found in the screw-retained FPDs bonded to gold cylinders (s-bon; Fig 6c), which displayed values of up to 20 MPa in the cortical area and approximately 3 MPa at the apex. The cementable FPDs made on master casts obtained from repositioning technique impressions (c-rep) exhibited stresses of around 5 to 8 MPa in the cortical area and around 2 MPa below the implant in the trabecular bone (Fig 6a).

A comparison with a clinically realistic situation with 200-N axial loading is depicted in Fig 7. The stresses in the cortical layer and the apical area were approximately 20 MPa and 5 MPa, respectively. The symmetrical stress pattern at the lateral aspect can be clearly seen.

DISCUSSION

In accordance with the strain gauge values obtained in vivo, the FE images show low von Mises stress in the cervical portions of the cement-retained samples. In the 2 groups of screw-retained FPDs, the stress concentration was considerably increased in the corresponding area. In the apical area of the implant, only low von Mises stresses were found in the bone for all 3 FPD groups. Two different scales were used for cortical and trabecular bone, allowing for a detailed illustration of the stress situation in each case. In order to associate the findings with a clinical framework, a comparison with vertical loading of 200 N on a single implant was performed. The FE image of this clinically feasible loading situation indicates that FPD fixation in the 2 screw-retained groups examined (s-cas, s-bon) induces a magnitude of stress in the bone similar to that caused by a loading force of 200 N, whereas the cement-retained FPDs exhibited a more favorable stress situation. In the assumption that a vertical load of 200 N does not cause bone damage,[27] it may be concluded from the results presented that the precision of fit which can be obtained through standard laboratory and clinical methods of superstructure fabrication would suffice to produce restorations that also do not cause bone damage.

The question of passive fit should therefore be reevaluated, since both the good long-term performance of implant-supported FPDs[28] and the FEA performed indicate that a certain level of misfit appears to be tolerated by the bone.

Set-up Critique

The strain levels measured in vivo may be slightly higher than in restorations made in standard clinical procedures, since all of the FPDs used in this study were fabricated on the basis of impressions taken from the in vitro measurement model.[13] Thus, the strain levels measured in vivo resulted not only from inaccuracies in the fabrication process but also from inevitable shortcomings in the transfer from the patient situation to the measurement model.

For reasons of comparability, the screw-retained restorations bonded to gold cylinders (s-bon) were assembled on the measurement model and not in the oral cavity. Thus, inaccuracies inherent in the transfer from the patient to the measurement model can also be found in this group. It can be assumed that these superstructures would otherwise have shown lower strain development than the cementable samples.[13]

The difference between the in vitro[13] and in vivo strain levels may be due to the fact that the implants in the measurement model were anchored more rigidly than in the patient's maxilla. Periotest measurements showed values of –6 for model implants A and C and –5 for model implant B, whereas in the oral cavity, values of 0 for implant A, 1 for implant B, and 2 for implant C were recorded.

FE Critique

As it was the main purpose of the study to compare different FPD types regarding bone loading caused by the fixation of the restorations, a relative reference system had to be set up. Therefore, in the FE models, the implant-bone interface was described as direct contact. This might be seen as a simplification of reality but was sufficient for the purpose described. The FE simulation of the in vivo pontic values was obtained by applying a vertical force, which is approximately commensurate with closing a vertical gap between the implant and superstructure. Although other types of force application, such as horizontal loading, would also be possible, the method of modeling chosen here would seem to be an acceptable approach. The virtual gap sizes to be closed in the FE models for simulation of the SG values were also taken from the calibration model and ranged from 1.3 μm to 6.9 μm. These values seem very clinically acceptable, as much higher values have been reported even with single-crown restorations.[29] This may be seen as a further indication of the method's suitability.

To illustrate bone loading, von Mises equivalent stress was used, as it is the standard method of illustrating stress and allows for comparisons between this study and related publications.[8,22,25] As no experiment-based mechanical failure data exist for multiaxial bone loading,[30] clinically relevant evaluation of the stresses calculated for the various FPD groups has not been feasible thus far. For this reason, said stresses were compared to axial loading of 200 N, which may be seen as being equivalent to an actual physiologic loading situation. With the symmetrical arrangement of the generated FE models, only 1 of the 2 strain gauge values could be simulated in a specific calculation. In order to avoid underestimating the risk of loss of osseointegration, the higher measurement value of the 2 in vivo pontic SG values for each FPD group was chosen.

CONCLUSIONS

In vivo strain gauge measurements and FEA demonstrated that the fixation of 5-unit FPDs and an axial load of 200 N can evoke static implant loading of comparable heights. From the data presented, there did not appear to be a risk of bone damage solely through superstructure fixation.

ACKNOWLEDGMENTS

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