Bone Adaptation Induced by Non–Passively Fitting Implant Superstructures: A Randomized Clinical Trial

Matthias Karl, Priv-Doz, Dr Med Dent[1]/Thomas D. Taylor, DDS, MSD[2]

Purpose: *Passive fit of implant-supported restorations is difficult to achieve. The aim of this randomized clinical trial was to test the null hypotheses that a reduction in misfit strain does not occur over time, regardless of the initial strain level, and that changes in prosthesis-induced bone strain do not differ between restorations with two different levels of fit.* ***Materials and Methods:*** *Twenty edentulous sites were restored with screw-retained fixed restorations on two implants either cast in one piece (misfit) or assembled by an intraoral bonding procedure (fit). The restorations had a bar-shaped pontic onto which a strain-gauged metal plate could be fixed. Repeated strain gauge measurements on patient-specific in vitro resin models and on the implants intraorally were performed every 4 weeks for a period of 6 months. Statistical analysis was based on Kruskal-Wallis tests, t tests, Welch two-sample t test (α = .05), and linear regression analysis.* ***Results:*** *No reduction in misfit strain could be observed in vitro, indicating that alterations in prosthetic fit had not occurred in any restoration (Kruskal-Wallis; P > .05). Initial strain levels varied widely and differed significantly between fit and misfit restorations (t test; P = .0032). Regrouping the restorations with respect to a threshold strain level of 100 μm/m resulted in 10 fit and 9 misfit restorations; 1 restoration had to be excluded from analysis due to a malfunctioning strain gauge. Seven fit restorations and five misfit restorations showed strain reduction in vivo based on linear regression, while percentage strain reduction did not differ between groups (Welch two-sample t test; P = .8186).* ***Conclusion:*** *Within the limitations of this randomized clinical trial characterized by an observation period of 6 months and only healthy subjects being enrolled, bone adaptation around statically and dynamically loaded implants occurred, causing a decrease in misfit strain evoked by non–passively fitting prostheses. For maintaining osseointegration of dental implants, passivity of fit of multiunit restorations seems not to be as critical as previously thought.* Int J Oral Maxillofac Implants 2016;31:369–375. doi: 10.11607/jomi.4331

Keywords: *bone adaptation, misfit stress, passive fit, randomized clinical trial, strain gauge*

Osseointegrated dental implants are rigidly anchored in alveolar bone, thereby limiting their resilience as compared with natural teeth.[1] To avoid overloading of the implant-bone interface, it has been postulated that multiunit implant-supported restorations should exhibit a passive fit.[2–5] If that goal is not achieved, superstructure connection causes static loading of the restorations, the supporting implants, and bone. Besides technical complications[6] such as screw loosening and component fracture, biologic problems including bone loss have also been attributed to a lack of passive fit.[7] However, the term "passive fit" has never been defined in a quantitative biomechanical way, and clinical methods for evaluating implant framework fit have been proven not to provide objective results.[8]

Since the level of fit of a specific restoration is determined by the level of accuracy achieved during its fabrication process, single aspects including impression making, master cast fabrication, and ceramic veneering have been studied extensively.[1,9] Also, the question as to whether screw retention or cement retention would lead to less static loading has been addressed,[1,10] and advanced fabrication methods such as intraoral luting of frameworks have been described.[11] More recently, the advent of computer-aided design/computer-assisted manufacturing (CAD/CAM) has been shown to result in restorations with greater levels of accuracy.[9] Regardless of the efforts made during superstructure fabrication, it has been proven that a totally passive restoration cannot be achieved with currently available methods and materials.[12]

[1]Associate Professor, Department of Prosthodontics, University of Erlangen-Nuremberg, Erlangen, Germany.
[2]Professor and Head, Department of Reconstructive Sciences, University of Connecticut Health Center, Farmington, Connecticut, USA.

This paper was presented at the 30th Annual Meeting of the Academy of Osseointegration in San Francisco, California.

Correspondence to: Dr Matthias Karl, Department of Prosthodontics, University of Erlangen-Nuremberg, Glueckstrasse 11, 91054 Erlangen, Germany. Fax: +49-9131-853 6781. Email: Matthias.Karl@uk-erlangen.de

©2016 by Quintessence Publishing Co Inc.

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

Despite the inevitable lack of passivity, good long-term results for conventional implant-supported prostheses have been reported.[6,13] Consequently, different authors questioned the need for passive fit, postulating that a minimum level of distortion and associated stress that is biologically acceptable would be sufficient.[14,15]

When focusing on the biologic aspects of static implant loading and misfit strain caused by non–passively fitting superstructures, ie, the reaction of bone surrounding the supporting implants, Wolff's law and the mechanostat theory[16,17] associated with it seem pertinent.[18,19] As a consequence, the loading type and magnitude acting on a living tissue would affect its architecture to adapt to a specific environment. Reduced masticatory function in edentate people, for instance, leads to structural changes in the edentulous site[20] and in the mandibular condyle with respect to trabecular structure, bone density, and, subsequently, mechanical properties.[21,22] Similarly, the concept of bone adaptation has also been discussed with respect to dental implants.[23,24]

Various studies have been conducted in the orthodontic field showing that the use of dental implants for orthodontic anchorage, with comparably low levels of static load, causes implant displacement and bone remodeling without compromising osseointegration.[25–28] Different authors also attempted to evaluate bone response exclusively resulting from static implant loading caused by the fixation of prostheses with different levels of fit.[29–33] While all authors found the implants to remain stable, differences for unloaded implants could not be established.[29–34] A possible explanation may be seen in the fact that the implants were not loaded dynamically despite dynamic loading constituting the essential stimulus for bone adaptation.[35–37] Based on an in vivo pilot study[38] and an associated finite element analysis,[39] it was hypothesized that static implant loading in a physiologic range, being superimposed by dynamic masticatory loads, would cause adaptational changes in the implant-bone complex, which would lead to implant site displacement in a direction resulting in a decrease of measurable misfit strains.

The aim of this randomized clinical trial was to test the null hypotheses that a reduction in strain levels does not occur, regardless of the level of strain found, and that changes in prosthesis strain do not differ between restorations with two different levels of fit.

MATERIALS AND METHODS

Clinical Aspects

Following ethics commission approval (University of Erlangen-Nuremberg, Medical faculty, approval number 3933) and registration under Current Controlled Trials (http://www.controlled-trials.com; ISRCTN 51714535), 16 patients with one free-end situation and 2 patients with two free-end situations each were recruited. All patients had been treatment planned for receiving two implants per site supporting a three-unit fixed dental prosthesis (FDP) and met the following inclusion criteria:

- No general contraindications for implant rehabilitation
- No impaired general health conditions (uncontrolled diabetes, immunosuppression)
- No diseases and medications affecting bone quality (osteoporosis, Morbus Paget, bisphosphonate therapy)
- No untreated periodontal disease

The participants were randomly divided into two groups: "fit" and "misfit". Randomization was done by an independent individual based on enrollment numbers and a group randomization protocol.[40] In each group of four patients, two received well-fitting restorations and two received misfitting restorations. Those patients presenting with bilateral free-end situations received one well-fitting and one misfitting restoration each. In the fit group, the restorations were fabricated according to a previously established intraoral bonding protocol that has been proven to evoke only a minimum of static implant loading.[1,11] In the misfit group, the restorations were fabricated by one-piece casting.[1] All restorations were assessed with currently accepted clinical methods, including a single screw test, and were deemed to be clinically acceptable.

In cases of insufficient bone volume, bone augmentation was carried out using autogenous bone from intraoral donor sites in a separate procedure prior to implant placement. In all cases, 4.1 × 10-mm tissue-level screw-type implants (Straumann Standard Plus RN, Straumann) were inserted, with the exception of three sites, where in addition to a 4.1 × 10-mm implant, a 4.1 × 8-mm or a 4.1 × 14-mm implant was placed. Maxillary implants were allowed to heal for 24 weeks, and mandibular implants were allowed to heal for 12 weeks. In total, 10 restorations were placed on maxillary implants, and 10 restorations were placed on mandibular implants. Subsequently, implant-level impressions were made using custom trays and polyether impression material (Impregum, 3M Deutschland, 3M Espe). Following standard clinical and laboratory protocols, three-unit screw-retained restorations were fabricated using a high-noble alloy (Wegold Norm, Wegold Edelmetalle). The restorations consisted of regular crowns on the implant abutments with anatomical occlusal contacts and a bar-like pontic area without occlusal contacts onto which a metal plate could be attached using screws. For each patient,

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

a resin model with original implants was manufactured (Orthocryl, Dentaurum). Unidirectional strain gauges (1-LY11-0.6/120, Hottinger Baldwin Messtechnik) were attached to the model material mesially and distally adjacent to the anterior and posterior implant and on the metal plate with the sensing elements oriented in the mesial-distal direction (Fig 1a). The strain gauges on the model material were named according to their position (Am = mesial strain gauge at anterior implant, Ad = distal strain gauge at anterior implant, Pm = mesial strain gauge at posterior implant, Pd = distal strain gauge at posterior implant). The restorations were based on abutments for screw-retained restorations (synOcta screw-retained, Straumann), which remained in place both on the resin model and in the patient's mouth for the duration of the study.

At each measurement session (day of superstructure delivery and after 1, 2, 3, 4, 5, and 6 months), the FDP was removed from the oral cavity, the strain gauge equipped metal plate was attached, and in vitro strain measurements were performed on the resin model during superstructure fixation with a torque of 15 Ncm applied by a surgical motor (NSK Surgic XT, NSK Europe). A measurement amplifier (Spider 8, Hottinger Baldwin Messtechnik) and analyzing software (BEAM for Spider, AMS) were used for measuring strain development during FDP fixation while the final strain values after 3 minutes were recorded for analysis. A total of three in vitro strain measurements were carried out at each measurement session. In vivo strain development at the pontic site during superstructure fixation with a torque of 15 Ncm was measured for a period of 10 minutes recording the lowest strain value after screw tightening for analysis (Fig 1b). Temperature measurements were carried out simultaneously and used for identifying potential effects on the strain gauge signals caused by temperature changes. Upon completion of a measurement session, the strain gauge equipped metal plate was removed, while the FDP remained on the implants in the patient's mouth for the time period between two measurement sessions.

Implant stability was monitored throughout the experiment using resonance frequency analysis (Osstell, Osstell), and panoramic radiographs were made after implant insertion, after delivery of the restoration, and upon completion of the experiment (Fig 2).

Statistical Analysis

The in vitro strain values measured in a specific patient at Am, Ad, Pm, and Pd were pooled for each measurement session. Statistical comparisons between different time points were carried out using nonparametric Kruskal-Wallis tests neither requiring a normal distribution of measurement values nor any assumptions with respect to variances. The level of significance for these comparisons was set at $\alpha = .05$. All in vitro strain values measured in a specific patient at the pontic site were averaged for obtaining a reference value. A correction factor was calculated for each measurement session by dividing the mean in vitro pontic value of a specific session with the reference value. The in vivo measured strain value of the same session was subsequently adjusted, applying the session-specific correction factor. For describing changes in strain development over time, it was assumed that the corrected in vivo measurement values could be adequately described by linear regression curves. Studentized residuals with a confidence interval of 85% were subsequently used for excluding measurement outliers constituting a physiologically impossible increase in strain development. For comparing initial in vivo strain development between fit and misfit restorations, *t* test statistics were performed, while for comparing percentage changes in strain development, Welch two-sample *t* test statistics were applied. For both tests, the level of significance was set at $\alpha = .05$.

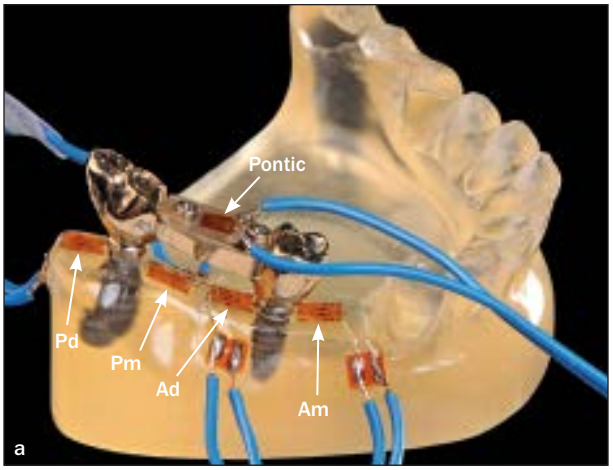

Fig 1a *(above)* In vitro resin model of a patient situation with strain gauges positioned mesially and distally adjacent to the anterior and posterior implants. The strain gauges were named according to their position (Am = mesial strain gauge at anterior implant, Ad = distal strain gauge at anterior implant, Pm = mesial strain gauge at posterior implant, Pd = distal strain gauge at posterior implant). At each session, the FDP was fixed on the in vitro model for strain measurements. A one-piece cast restoration is shown.

Fig 1b *(right)* Situation of an intraorally bonded FDP fixed in the oral cavity of a patient for in vivo strain measurements at the pontic site.

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

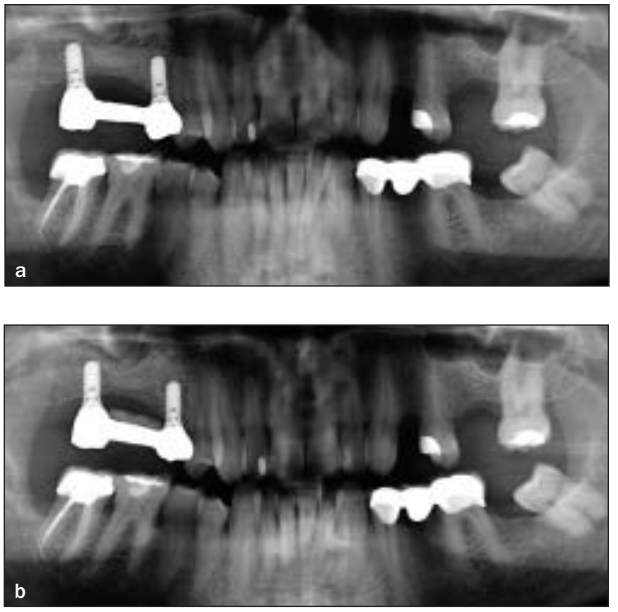

Fig 2 Panoramic radiographs of patient 18 showing a misfit restoration on two implants in the right maxilla *(a)* at the beginning of the study period and *(b)* after completion of the study.

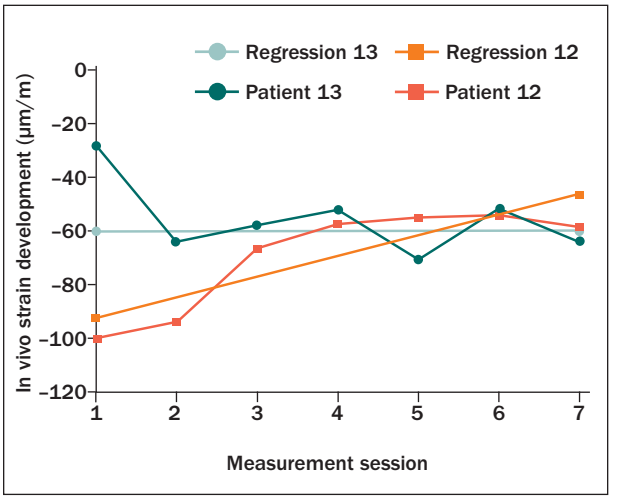

Fig 3 Exemplary graphs showing the in vivo strain values and linear regression curves obtained in two patients. In patient 12, reduction in strain development is noted, while in patient 13, no change in strain development occurs over time.

Table 1 Percentage Changes in Strain Development Over Time for All Patients Based on the Initial and Final Value of the Regression Curve

Patient	Restoration type	Re-grouping	Initial	Final	Decrease in %
1	Misfit	Misfit	–246.32	–111.90	55%
2	Misfit	Misfit	–140.85	–163.86	–16%
3	Misfit	Misfit	–156.50	–119.08	24%
4	Misfit	Misfit	–354.00	–437.98	–24%
5	Fit	Misfit	136.30	124.90	8%
6	Misfit	Misfit	238.60	99.60	58%
7	Misfit	Misfit	–402.26	–441.50	–10%
8	Misfit	Misfit	–507.80	–589.42	–16%
9	Misfit	Misfit	357.22	258.98	28%
10	Fit	Fit	57.71	34.56	40%
11	Fit	Fit	–13.19	–22.05	–67%
12	Misfit	Fit	–92.50	–46.91	49%
13	Misfit	Fit	–60.51	–60.30	0%
14	Fit	Fit	35.87	22.14	38%
15	Misfit	Fit	–33.64	–30.54	9%
16	Fit	Fit	–67.70	–22.93	66%
17	Fit	Fit	–82.83	–85.03	–3%
18	Misfit	Fit	88.23	31.66	64%
19	Fit	Fit	23.29	–9.95	100%

RESULTS

The clinical trial could be completed without losing any of the implants and without any adverse event. All implants maintained their specific level of stability achieved during osseointegration, showing constant peri-implant bone levels in the panoramic radiographs. However, in one patient who was randomized into the misfit group, a malfunction of the pontic strain gauge occurred after four measurement sessions, leading to a reversed strain gauge signal. This patient was excluded from further analysis.

In vitro strain development recorded mesially and distally adjacent to the implants supporting a specific restoration did not change significantly over time (Kruskal-Wallis tests; $P > .05$) in all patients. Therefore, it could be assumed that no changes in the precision of fit of any restoration had occurred due to wear phenomena at the prosthetic interface.

Absolute corrected initial in vivo strain development ranged from 1.06 µm/m to 135.59 µm/m for fit restorations and from 40.80 µm/m to 533.08 µm/m for misfit restorations. The difference between both groups was statistically significant (*t* test; $P = .0032$). Despite being randomized as a misfit restoration, low levels of initial strain development were also seen in the misfit group. As such, the restorations were regrouped according to actual strain development using a threshold value of 100 µm/m for fit restorations. This threshold value was chosen based on strain readings obtained in this study. Consequently, the

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

misfit group comprised 9 restorations, and the fit group comprised 10 restorations. Percentage changes in strain development were calculated for each patient (Table 1) using the initial and final values of the regression curves describing the in vivo measured strains (Fig 3). A reduction in strain development over time was observed in 7 out of 10 fit restorations and in 5 out of 9 misfit restorations. Consequently, the first null hypothesis, that no change in strain development would occur, was rejected. No significant difference in percentage change in strain development over time was found between fit and misfit restorations (Welch two-sample *t* test; $P = .8186$), thereby accepting the second null hypothesis. While there were subjects in both groups in which no change in strain development occurred over time, no threshold value could be determined below which reduction in strain development did not occur.

DISCUSSION

Study Design

This randomized clinical trial was designed based on the experiences made in a pilot study on the same topic using repeated strain measurements on an implant-supported, screw-retained overdenture bar.[38,39] For optimizing measurement accuracy, a metal plate that could be reproducibly attached to the pontic of a fixed restoration was equipped with a strain gauge instead of reattaching a new strain gauge at each measurement session as was done in the pilot study. Nevertheless, the sensitivity of the sensor varied between measurement sessions, requiring a correction factor for compensation. Furthermore, a unidirectional sensor was utilized for capturing strains caused by three-dimensional distortions inherent in a specific restoration[41] where different compositions of spatial errors could cause the same strain gauge signal. The purpose of utilizing fixed restorations instead of an implant-retained overdenture was to increase dynamic loading of the implants during mastication, since it has been shown that dynamic rather than static loads induce bone adaptation.[35–37] This seems to be the most important reason why previous attempts of determining bone adaptation in animal studies failed,[29,30] since functional loads can only be well controlled in humans. Nevertheless, the study design chosen represents a compromise of technical feasibility and theoretical demand. In particular, the sensors did not capture strains in the buccolingual direction, and the construction of the restorations with a detachable sensor absorbed an unknown percentage of the strains present in a specific situation.

Statistical Analysis

The design of this study also led to some limitations in statistical data analysis. The in vitro strain measurements can be considered as repeated measurements of a specific FDP on a specific resin model. As no distribution pattern with respect to the random deviations from the mean values could be observed in any of the restorations, thereby indicating independency of measurement values, the analysis performed using Kruskal-Wallis tests appears feasible. Given that only one in vivo measurement value was available for each patient at a specific time point, the adequacy of a linear regression for describing strain development over time could not be proven by statistical means. Furthermore, the confidence interval of 85% for excluding in vivo measurement values was chosen with respect to the sensitivity of the strain gauges instead of pure statistical considerations, which would have required a Bonferroni correction.

In one case (patient 19), the inclination of the regression curve based on comparatively small in vivo strain values led to a switch from a positive initial value to a negative final value. Mechanically, this would imply a switch from tensile to compressive deformation, which is impossible with the given setup. For this reason, a 100% reduction in strain development was reported.

Clinical Aspects

For ethical reasons and to avoid the risk of overloading the implant-bone interface, one-piece cast restorations fabricated according to currently accepted protocols were manufactured. Both fit and misfit restorations showed considerable variation in initial strain development, necessitating reclassification based on the strain gauge readings. A further variable was the dimensions of the bar-shaped pontic used in the FDPs, which could not be standardized, although one technician fabricated all of the restorations with one specific alloy.

Component wear at the restorative interface[3] could have also led to a reduction in static loading, but it could be excluded since consistent strain values were recorded in the in vitro measurements for each restoration over time. Hence, only bone remodeling could have caused changes in the strain levels measured on the restorations in vivo.

One specific implant type with a 4.1-mm diameter and 10-mm length was used in all patients with the exception of three sites, where 8- and 14-mm-long implants had to be used in combination with 10-mm-long implants. Out of these cases, one patient who received an 8-mm implant showed no strain reduction, while in the remaining two patients, a clear strain reduction was observed, indicating that implant

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

length has no influence on bone adaptation. Similarly, no effect of age, sex, and bone quality as determined by different mandibular and maxillary areas could be seen. On the contrary, thresholds for bone adaptation[27,28] above which strains are reduced and below which strains remain constant seem to be highly patient-specific, since in some instances with high strain levels no reduction was seen, whereas in cases of low initial strain a clear reduction in static loading was observed. However, it seems to be impossible to exactly determine the strains acting on the bone surrounding the implants based on the measurements conducted. Instead of using direct strain measurements on the bone surface adjacent to the supporting implants, which would have been desirable,[19,42] this study design used indirect measurements on implant-supported restorations. Consequently, only qualitative results can be derived, while the numerical threshold values for bone adaptation with a lower threshold of 100 to 300 μm/m and an upper threshold of 1,500 to 3,000 μm/m[16,17] could not be verified.

Despite the limitations of this experiment, it can be stated that an absolute passive fit in the sense of 0 μm/m being recorded on the pontic of a restoration is impossible to achieve, regardless of the fabrication technique employed and the restorative material chosen.[1,9] From the perspective of bone physiology, it appears that an absolute passive fit is not needed since bone adaptation will cause implant displacement into a position that reduces misfit stress.[39] Although not tested in the present study, it may be anticipated that misfitting restorations used in immediate loading protocols lead to pronounced bone adaptation and implant movement since the implant-bone interface during healing can be deformed more easily.[4,33]

However, it has to be kept in mind that the clinical situations chosen for this study were well selected. Only healthy patients were included, and as such, it cannot be inferred that bone adaptation would occur to the same extent in medically compromised individuals. Splinting of only two implants was chosen, as it represents a clinically very common situation. In cases where more implants are splinted, higher levels of misfit stress would be anticipated based on comparative studies in this field.[1] Although the study period was only 6 months, the adaptational processes observed seemed to reach a steady state after that period, with only minor changes occurring at the end (Fig 3, red curve). As such, it might be anticipated that no further reduction in strain development would be observed thereafter. Various authors have shown that technical complications are frequently seen in implant-supported superstructures.[6,10] With the study design applied, no conclusions can be made with respect to technical complications, and no threshold values can be derived from the data presented.

CONCLUSIONS

Assuming a lower stress threshold for misfit stress exists below which no bone adaptation occurs since the body tolerates these stress levels, restorations falling into this category should be defined as showing "passive fit." Restorations showing greater levels of misfit stress that do not cause overload and bone resorption but lead to bone adaptation and subsequently less misfit should be defined as showing "biologically acceptable fit." It currently seems to be impossible to numerically define at which stress levels the thresholds postulated are located.[7] All of the restorations used in this study seem to fall in either of these categories, although rather simplistic impression making and fabrication techniques such as one-piece casting have been employed that have been shown to be less accurate compared with current CAD/CAM procedures.[9] Taking into account that restorations with a biologically acceptable fit show sufficient levels of precision and that operator-related factors, particularly during impression making, predominantly determine the levels of misfit inherent in a specific restoration, implant components with high levels of precision seem not to be necessary. Furthermore, cost-intensive fabrication methods, such as the intraoral luting technique applied here, do not necessarily lead to a better biologic performance as compared with simple fabrication methods such as one-piece casting. However, it cannot be inferred from this study that technical complications do not occur in non–passively fitting restorations.[6,7,13]

ACKNOWLEDGMENTS

This study was supported by a grant from the ITI Foundation for the Promotion of Oral Implantology, Basel, Switzerland. The authors wish to thank ZTM Georg Schmidtler, Schmidtler Dental Laboratories, Schoenthal, Germany for fabricating all restorations and Dr Friedrich Graef, Department of Mathematics, University of Erlangen-Nuremberg for statistical data analysis. The authors reported no conflicts of interest related to this study.

REFERENCES

1. Karl M, Winter W, Taylor TD, Heckmann SM. In vitro study on passive fit in implant-supported five-unit fixed partial dentures. Int J Oral Maxillofac Implants 2004;19:30–37.
2. Cheshire PD, Hobkirk JA. An in vivo quantitative analysis of the fit of Nobel Biocare implant superstructures. J Oral Rehabil 1996; 23:782–789.
3. Hecker DM, Eckert SE. Cyclic loading of implant-supported prostheses: Changes in component fit over time. J Prosthet Dent 2003;89:346–351.
4. Yilmaz B, Suarez C, McGlumphy E. Correction of misfit in a maxillary immediate metal-resin implant-fixed complete prosthesis placed with flapless surgery on four implants. Int J Oral Maxillofac Implants 2011;26:e23–e28.

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

5. Abduo J, Judge RB. Implications of implant framework misfit: A systematic review of biomechanical sequelae. Int J Oral Maxillofac Implants 2014;29:608–621.
6. Brägger U, Aeschlimann S, Bürgin W, Hämmerle CH, Lang NP. Biological and technical complications and failures with fixed partial dentures (FPD) on implants and teeth after four to five years of function. Clin Oral Implants Res 2001;12:26–34.
7. Taylor TD. Prosthodontic problems and limitations associated with osseointegration. J Prosthet Dent 1998;79:74–78.
8. Kan JY, Rungcharassaeng K, Bohsali K, Goodacre CJ, Lang BR. Clinical methods for evaluating implant framework fit. J Prosthet Dent 1999;81:7–13.
9. Karl M, Taylor T. Effect of material selection on the passivity of fit of implant-supported restorations created with computer-aided design/computer-assisted manufacture. Int J Oral Maxillofac Implants 2011;26:739–745.
10. Michalakis KX, Hirayama H, Garefis PD. Cement-retained versus screw-retained implant restorations: A critical review. Int J Oral Maxillofac Implants 2003;18:719–728.
11. Karl M, Graef F, Taylor T, Heckmann SM. Stability of screw-retained implant-supported fixed dental prostheses bonded to gold cylinders. Int J Prosthodont 2009;22:604–606.
12. Wee AG, Aquilino SA, Schneider RL. Strategies to achieve fit in implant prosthodontics: A review of the literature. Int J Prosthodont 1999;12:167–178.
13. Pjetursson BE, Tan K, Lang NP, et al. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clin Oral Implants Res 2004;15:625–642.
14. Tan KB. The clinical significance of distortion in implant prosthodontics: Is there such a thing as passive fit? Ann Acad Med Singapore 1995;24:138–157.
15. Jemt T, Book K. Prosthesis misfit and marginal bone loss in edentulous implant patients. Int J Oral Maxillofac Implants 1996;11:620–625.
16. Frost HM. Bone "mass" and the "mechanostat": A proposal. Anat Rec 1987;219:1–9.
17. Frost HM. A 2003 update of bone physiology and Wolff's Law for clinicians. Angle Orthod 2004;74:3–15.
18. Garetto LP, Chen J, Parr JA, Roberts WE. Remodeling dynamics of bone supporting rigidly fixed titanium implants: A histomorphometric comparison in four species including humans. Implant Dent 1995;4:235–243.
19. Al Nazer R, Lanovaz J, Kawalilak C, Johnston JD, Kontulainen S. Direct in vivo strain measurements in human bone—a systematic literature review. J Biomech 2012;45:27–40.
20. Bassi F, Procchio M, Fava C, Schierano G, Preti G. Bone density in human dentate and edentulous mandibles using computed tomography. Clin Oral Implants Res 1999;10:356–361.
21. Giesen EB, Ding M, Dalstra M, van Eijden TM. Reduced mechanical load decreases the density, stiffness, and strength of cancellous bone of the mandibular condyle. Clin Biomech (Bristol, Avon) 2003;18:358–363.
22. Giesen EB, Ding M, Dalstra M, van Eijden TM. Changed morphology and mechanical properties of cancellous bone in the mandibular condyles of edentate people. J Dent Res 2004;83:255–259.
23. Stanford CM, Brand RA. Toward an understanding of implant occlusion and strain adaptive bone modeling and remodeling. J Prosthet Dent 1999;81:553–561.
24. Rungruanganunt P, Taylor TD, Eckert SE, Karl M. The effect of static load on dental implant survival: A systematic review. Int J Oral Maxillofac Implants 2013;28:1218–1225.
25. Melsen B, Lang NP. Biological reactions of alveolar bone to orthodontic loading of oral implants. Clin Oral Implants Res 2001;12:144–152.
26. Trisi P, Rebaudi A. Progressive bone adaptation of titanium implants during and after orthodontic load in humans. Int J Periodontics Restorative Dent 2002;22:31–43.
27. Cattaneo PM, Dalstra M, Melsen B. Analysis of stress and strain around orthodontically loaded implants: An animal study. Int J Oral Maxillofac Implants 2007;22:213–225.
28. Hsieh YD, Su CM, Yang YH, et al. Evaluation on the movement of endosseous titanium implants under continuous orthodontic forces: An experimental study in the dog. Clin Oral Implants Res 2008;19:618–623.
29. Michaels GC, Carr AB, Larsen PE. Effect of prosthetic superstructure accuracy on the osteointegrated implant bone interface. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1997;83:198–205.
30. Carr AB, Gerard DA, Larsen PE. The response of bone in primates around unloaded dental implants supporting prostheses with different levels of fit. J Prosthet Dent 1996;76:500–509.
31. Jemt T, Lekholm U, Johansson CB. Bone response to implant-supported frameworks with differing degrees of misfit preload: In vivo study in rabbits. Clin Implant Dent Relat Res 2000;2:129–137.
32. Jemt T, Lekholm U. Measurements of bone and frame-work deformations induced by misfit of implant superstructures. A pilot study in rabbits. Clin Oral Implants Res 1998;9:272–280.
33. Duyck J, Vrielinck L, Lambrichts I, et al. Biologic response of immediately versus delayed loaded implants supporting ill-fitting prostheses: An animal study. Clin Implant Dent Relat Res 2005;7:150–158.
34. Duyck J, Rønold HJ, Van Oosterwyck H, et al. The influence of static and dynamic loading on marginal bone reactions around osseointegrated implants: An animal experimental study. Clin Oral Implants Res 2001;12:207–218.
35. Turner CH. Three rules for bone adaptation to mechanical stimuli. Bone 1998;23:399–407.
36. Duncan RL, Turner CH. Mechanotransduction and the functional response of bone to mechanical strain. Calcif Tissue Int 1995;57:344–358.
37. Halldin A, Jimbo R, Johansson CB, et al. The effect of static bone strain on implant stability and bone remodeling. Bone 2011;49:783–789.
38. Karl M, Graef F, Heckmann SM, Taylor T. A methodology to study the effects of prosthesis misfit over time: An in vivo model. Int J Oral Maxillofac Implants 2009;24:689–694.
39. Winter W, Taylor T, Karl M. Bone adaptation induced by non-passively fitting implant superstructures: A finite element analysis based on in vivo strain measurements. Int J Oral Maxillofac Implants 2011;26:1288–1295.
40. Heckmann SM, Hujoel P, Habiger S, et al. Zinc gluconate in the treatment of dysgeusia—a randomized clinical trial. J Dent Res 2005;84:35–38.
41. Winter W, Möhrle S, Holst S, Karl M. Bone loading caused by different types of misfits of implant-supported fixed dental prostheses: A three-dimensional finite element analysis based on experimental results. Int J Oral Maxillofac Implants 2010;25:947–952.
42. Kan JP, Judge RB, Palamara JE. In vitro bone strain analysis of implant following occlusal overload. Clin Oral Implants Res 2014;25:e73–e82.

© 2016 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY.
NO PART MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.