Digital image correlation analysis of the load transfer by implant-supported restorations

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ARTICLE INFO

Article history:
Accepted 14 February 2011

Keywords:
Image correlation
Implants
Load transfer
Prosthodontics

ABSTRACT

This study compared splinted and non-splinted implant-supported prosthesis with and without a distal proximal contact using a digital image correlation method. An epoxy resin model was made with acrylic resin replicas of a mandibular first premolar and second molar and with threaded implants replacing the second premolar and first molar. Splinted and non-splinted metal–ceramic screw-retained crowns were fabricated and loaded with and without the presence of the second molar. A single-camera measuring system was used to record the in-plane deformation on the model surface at a frequency of 1.0 Hz under a load from 0 to 250 N. The images were then analyzed with specialist software to determine the direct (horizontal) and shear strains along the model. Not splinting the crowns resulted in higher stress transfer to the supporting implants when the second molar replica was absent. The presence of a second molar and an effective interproximal contact contributed to lower stress transfer to the supporting structures even for non-splinted restorations. Shear strains were higher in the region between the molars when the second molar was absent, regardless of splinting. The opposite was found for the region between the implants, which had higher shear strain values when the second molar was present. When an effective distal contact is absent, non-splinted implant-supported restorations introduce higher direct strains to the supporting structures under loading. Shear strains appear to be dependent also on the region within the model, with different regions showing different trends in strain changes in the absence of an effective distal contact.

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1. Introduction

The essential difference between natural teeth and osseointegrated implants is the absence of a periodontal ligament and thus limited micromovement in the latter, which consequently have less favorable distributions of forces (Weinberg, 1993) that concentrate at the crest of the ridge (Rieger et al., 1990). Natural teeth can move by up to 100 μm within its surrounding periodontal ligament, allowing for a certain degree of misfit of a fixed partial denture (FPD). In contrast, an osseointegrated implant has limited movement, less than 10 μm, due solely to bone elasticity (Solnit and Schneider, 1998). Occlusal over-load may induce bone resorption which can lead to marginal bone loss and consequently to implant fractures and implant failure, primarily in the mandibular first molar region (Conrad et al., 2008; Quirynen et al., 1992; Rangert et al., 1995).

The ideal restoration of a partially edentulous space remains controversial as to the number of implants to be placed, the type

(Watanabe et al., 2000). Excessive forces at the implant–bone interface could lead to bone resorption (Riedy et al., 1997).

Numerous prosthetic options are available for dental restoration using multiple adjacent implants. Since complete passivity is difficult to achieve when using splinted restorations supported by multiple implants (Tiossi et al., 2008), some authors suggest restoring adjacent implants individually (Solnit and Schneider, 1998) to allow for a passive fit in the resulting restorations (Guechet et al., 2002). Splinting implant-supported restorations is primarily recommended for load sharing in distributing the antagonistic occlusal forces (Skalak, 1983) so as to reduce the strains transferred to the periodontium (Wylie and Caputo, 1991; Yang et al., 1999).
of implant–abutment connection to select, and whether screw- or cement-retained components should be used (Zarone et al., 2007). Studies are not available to guide clinicians sufficiently in evaluating and choosing many of the possible permutations and combinations of prosthetic designs. In fact, there is no evidence to suggest that implant survival or success is affected by the type of prosthesis (Weber and Sukotjo, 2007). There is thus no consensus on the best prosthetic design for partial rehabilitations with multiple adjacent implants to improve load distribution and decrease stress on the implant–bone interface, with the aim of increasing the implants’ survival rate. Although finite element models can simulate the mechanical behavior of many of these prosthetic designs, their validity as a predictive tool needs to be established using experimental data.

Digital image correlation (DIC) is an optical method that has been used to measure the flow of fluid and the surface strain distribution in materials testing (Li et al., 2009). In the latter application, a series of images of the specimen are taken using a charged-coupled device (CCD) camera during loading and the movements of individual spots on the surface of the specimen can be tracked and analyzed using specialist software to determine their displacements. The strains on the surface are then derived from the displacement fields (Li et al., 2009). Compared with strain gauges, therefore, DIC has the advantage of being able to provide full-field strain measurement.

The purpose of this in vitro study was to utilize DIC to analyze strains generated by implants in simulated supporting bone of 2 different prosthetic designs (splinted and non-splinted) under 2 clinical situations (presence or absence of distal interproximal contact to the restoration). Load transfer characteristics of the different prosthetic solutions were analyzed and compared. The null hypothesis was that there would be no differences in the strains generated in the supporting bone between the different prosthetic designs and between the different proximal contact conditions.

2. Material and methods

A model representing the bone block was fabricated from polymethylmethacrylate resin (Plexiglas®, Altuglas International, PA, USA) with dimensions of 68 × 25 × 15 mm (length, height and depth, respectively). Osteotomies were prepared and a patient-simulating arrangement comprising two Titaimax GT, Neodent, Curitiba-PR, Brazil) were embedded into the bone block model in the second premolar and first molar positions with cyanoacrylate adhesive (Super Bonder; Loctite Brasil Ltd., Itapevi-SP, Brazil) applied on their surface to represent complete integration (Akca and Cehreli, 2008). The model was completed with the placement of resin replicas of a first premolar and a second molar (Odontofix, Ribeirão Preto-SP, Brazil) using the same method as that for the implants.

Fig. 1. Experimental setup including the model, CCD camera, loading and supporting devices.

Fig. 2. Strains measured in the horizontal direction (e_{xx}). (A) Splinted crowns with second molar; (B) non-splinted crowns with second molar; (C) splinted crowns without second molar; and (D) non-splinted crowns without second molar. (a) Region of interest between molars and (b) region of interest between implants.
Accepted clinical and laboratory procedures were used to fabricate 2 sets of implant-supported crowns. Plastic burnout cylinders (Cilindro GT, Tilit, Neodent) were used to create a wax pattern for the crowns and a 1-mm cutback was made to allow for the addition of ceramic to the casting. A duplication silicone mold (Hard Duplex, CNG Soluções Protéticas, São Paulo_SP, Brazil) was placed over the FPD wax pattern to allow for multiple replications. Molten wax (Schuler Dental, Germany) was poured into the mold to fabricate 2 single-unit crowns and a 2-unit splinted FPD framework. The spruing, investment, burnout, and casting techniques were standardized and frameworks were cast in Ni–Cr–Ti alloy (Tilite Omega, Talladium Inc., USA). Patterns were sprued and invested individually in a phosphate-bonded investment (Castorit Super C, Dentaurum, Ispringen, Germany). Frameworks for the splinted group were positioned in the definitive model for laser welding. Specimens were later positioned in an optical comparator microscope (Nikon Corp., Tokyo, Japan) at 15 × magnification to ensure acceptable fit. Esthetic coatings were made using IPS dSign Ceramic (Dentin Body B4, Ivoclar Vivadent) with the aid of a silicone mold (Zetalaboral, Zhermack, SpA, Italy) to standardize application. The 2 design groups studied were: splinted metal–ceramic crowns (SC) and non-splinted metal–ceramic crowns (NS). Interproximal contacts between non-splinted crowns and between FPDs and resin teeth were adjusted using double-sided carbon foil (Accufilm II, Parkell, USA) to aim for an ideal contact tightness, which would allow an 8-μm tin foil shim to be dragged between the contacting surfaces without tearing (Guichet et al., 2002).

Implant-level pick-up impression posts (Neodent) were oriented on the implants and bonded together with acrylic resin (Pattern Resin LS, GC America Inc., USA) to allow a correct transfer of implant position to the epoxy model. A polyvinylsiloxane impression (Silicone Master, Talladium do Brasil, Curitiba, PR, Brazil) was made of the implant–teeth complex along with the entire acrylic block. Roots of the resin teeth were covered with a 0.3 mm layer of polyether impression material (Impregum F, 3 M ESPE, Seefeld, Germany) to simulate the periodontal ligament (Hohmann et al., 2007; Soares et al., 2005). The tooth replicas and implants were later positioned in the silicone mold. The resin experimental block was cast into this impression directly to the implants and teeth using a medium-modulus epoxy resin designed to simulate healthy bone (PL-2, Measurements Group, Raleigh, NC, USA) (Guichet et al., 2002; Karl et al., 2005). The second molar replica was later removed from the model to investigate the effect of its absence on the strains generated in the supporting structures. The medium-modulus resin cast was allowed to polymerize for 24 h prior to testing, according to manufacturer’s instructions.

The digital image correlation technique was used to measure strains generated on the surface of the resin models for the different FPD designs. The system (StrainMaster, LaVision Inc., Goettingen, Germany) included a CCD camera (Image Intense, LaVision Inc.) used for capturing the images of the deforming body and a specialist software package (DaVis 7.2, LaVision Inc.) for subsequent image analysis. The CCD camera had a resolution of 1039 × 1395 pixels and the maximum gray-scale count (intensity of gray coloring of a pixel) was 4095. The images were calibrated with a standard calibration plate provided by LaVision. The surface of the resin model facing the CCD camera was sprayed with a fine layer of black paint to produce irregular-shaped speckles for ease of tracking and analysis by the image correlation system (Li et al., 2009). A static non-impact punctiform load of up to 250 N was applied using a universal testing system (Materials Testing Solutions Systems, Eden Prairie, MN, USA) on the distal surface of the first implanted molar, and the model was supported at 2 points, giving a 3-point bending configuration to simulate that of half the arch (Fig. 1).

To measure the strains generated by the load on the model, images of the painted surface were taken at a frequency of 1 Hz until the 250 N load was reached. The first image was taken before load was applied, and the remaining images were compared to the first image to calculate the displacements on the surface of the model. Surface strains were then calculated from the displacements with the image correlation software (Davis 7.2, LaVision Inc.).

Regions of interest below the applied load were selected to analyze the strains generated. For the splinted FPD design, these were regions between the first and second molar and between the second premolar and first molar (Fig. 2A, regions a and b, respectively). The same regions of interest were selected for the model containing the non-splinted single unit crowns and the second molar (Fig. 2B) as well as that with the splinted FPD design and single unit crowns but without the presence of the second molar (Fig. 2C and D).

### Table 1
Mean (%) and standard deviation (SD) with Tukey’s test results of the repeated strain measurements in the horizontal direction (εxx).

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Between molars</th>
<th>Mean ± SD (Tukey’s test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>−0.14 ± 0.07A</td>
<td></td>
</tr>
<tr>
<td>Second</td>
<td>−0.15 ± 0.07A</td>
<td></td>
</tr>
<tr>
<td>Third</td>
<td>−0.14 ± 0.07A</td>
<td></td>
</tr>
</tbody>
</table>

q = 2.41849; p = 0.9172. Within columns, groups not connected by the same letter are significantly different.

**Fig. 3.** Repeated measurements of strains in the horizontal direction (εxx), between the molars.

**Fig. 4.** Calculations of strains in the horizontal direction (εxx): (A) Between the molars and (B) between the implants.
The strain distribution over the height of the resin block was analyzed for each region of interest. To reveal the difference in strain distribution between the different configurations, the effect of noise must be minimized. As a result, strain values averaged over 5 pixels of 0.5 mm wide each were calculated for each vertical position along the block height. The correct performance of the optical strain measurement system was verified by repeating the measurement 3 times for the model containing the splinted crowns and the second molar replica under the same loading conditions. The 3 measurements were statistically compared (ANOVA and Tukey’s test) to each other with specialist software (JMP 8.1, SAS Institute Inc., NC, USA) to verify repeatability of the results. The region used for comparison was between the molars and no significant differences were found between the repeated measurements (p > 0.05) (Table 1). In comparing the different groups in this study, differences in strain higher than those found in the repeatability measurements (Fig. 3) would be considered statistically significant (p < 0.05). Direct strains in the horizontal direction (εxx) and in-plane shear strains (εxy) were calculated and compared between the groups.

### 3. Results

Comparison between groups was focused on the upper compressive region down to the neutral axis of the resin block because differences were small in the lower tensile region. Direct strains (%) measured for the regions of interest in the horizontal direction (εxx) are illustrated in Fig. 2 and mean values and standard deviations between the first and second molars are shown in Fig. 4A and Table 2. Splinted crowns with the presence of a second molar (−0.15 ± 0.06) generated significantly lower strains when compared to non-splinted crowns without the second molar (−0.23 ± 0.08) (p < 0.05). No significant differences were found between the other groups in other pairings (p > 0.05): non-splinted crowns with the molar (−0.20 ± 0.08), and splinted crowns without the molar (−0.20 ± 0.08). When analyzing strains in the region between the 2 implants (second premolar and first molar), splinted crowns with the second molar present also produced significantly lower strain values (−0.04 ± 0.05) when compared to non-splinted crowns with an absent molar (−0.11 ± 0.04) (p < 0.05). No statistically significant differences were found between the other groups (p > 0.05) (Fig. 4B; Table 2).

Shear strains (εxy) were also calculated in this study (Fig. 5; Table 3). Results found in the first region of interest, i.e. between the molars, showed that shear strains were significantly higher when the second molar was absent (p < 0.05), irrespective of splinting or not splinting the crowns (without the molar: 0.14 ± 0.05 for splinted and 0.13 ± 0.06 for non-splinted; with the molar: 0.01 ± 0.03 for splinted and 0.02 ± 0.05 for non-splinted) (Fig. 6A). When analyzing the region between the implants, the opposite was found, i.e. significantly higher shear strain values were found when the second molar was present (p < 0.05), for both splinted and non-splinted crowns (without the molar: −0.08 ± 0.08 for splinted and −0.11 ± 0.10 for non-splinted; with the molar: 0.18 ± 0.08 for splinted and 0.20 ± 0.08 for non-splinted) (Fig. 6B).

#### Table 2

Mean (%) and standard deviation (SD) with Tukey’s test results of strain comparison in the horizontal direction (εxx).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Between molars Mean ± SD (Tukey’s test)</th>
<th>Between implants Mean ± SD (Tukey’s test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC with molar</td>
<td>−0.15 ± 0.06A</td>
<td>−0.04 ± 0.05A</td>
</tr>
<tr>
<td>NS with molar</td>
<td>−0.20 ± 0.08AB</td>
<td>−0.08 ± 0.05B</td>
</tr>
<tr>
<td>SC without molar</td>
<td>−0.20 ± 0.08AB</td>
<td>−0.08 ± 0.04B</td>
</tr>
<tr>
<td>NS without molar</td>
<td>0.23 ± 0.08B</td>
<td>−0.11 ± 0.04C</td>
</tr>
</tbody>
</table>

q=2.63784; p=0.0002. Within columns, groups not connected by the same letter are significantly different.

#### Table 3

Mean (%) and standard deviation (SD) with Tukey’s test results of in-plane shear strain comparison (εxy).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Between molars Mean ± SD (Tukey’s test)</th>
<th>Between implants Mean ± SD (Tukey’s test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC with molar</td>
<td>0.01 ± 0.03A</td>
<td>−0.18 ± 0.08A</td>
</tr>
<tr>
<td>NS with molar</td>
<td>0.02 ± 0.05A</td>
<td>−0.20 ± 0.08A</td>
</tr>
<tr>
<td>SC without molar</td>
<td>0.14 ± 0.05B</td>
<td>−0.08 ± 0.08B</td>
</tr>
<tr>
<td>NS without molar</td>
<td>0.13 ± 0.06B</td>
<td>−0.11 ± 0.10B</td>
</tr>
</tbody>
</table>

q=2.59558; p=0.0001. Within columns, groups not connected by the same letter are significantly different.

![Fig. 5. In-plane shear strains (εxy).](image-url)
4. Discussion

The data support rejection of the null hypothesis as there were statistically significant differences in the strains generated in the simulated supporting bone, depending on the prosthetic design and the presence or absence of an interproximal contact.

A digital image correlation technique was used to calculate and analyze strains generated by static non-impact loading on the surface of a bone simulant epoxy resin model with different implant-supported crown designs and clinical situations. Strain gauges have traditionally been used to determine strains on surfaces of bone and bone simulants (Akca and Cehreli, 2008; Karl et al., 2005; Yacoub et al., 2002), but they are limited to detecting strains in a small region (Karl et al., 2008). Additionally, a strain gage averages the strains measured over the gage length, possibly leading to lower readings than the actual values, and sensitivity of measurement to temperature changes is a cause of concern (Karl et al., 2008). An attractive feature of the digital image correlation method is that, instead of an average strain value generated on the small surface where the strain gage is positioned, full-field strains showing local details can be obtained for the whole surface of the model under observation. Shear strains can also be determined readily with this method, which is useful when considering implant failure because bone–implant interfacial shear strength is considerably inferior to the shear strength of homogenous cortical bone (Hansson, 2000).

When evaluating direct strains in the horizontal direction, both regions studied (a and b) presented similar results, i.e. were compressive up to the neutral axis. Splinted crowns with a second molar present transferred less strain to the supporting bone when compared to non-splinted crowns in the absence of the molar (Fig. 4, A and B). The other structures analyzed, i.e. non-splinted crowns with the second molar and splinted crowns without the molar, had no significant differences between them and other groups (Fig. 4, A and B). These results agree with those reported in another study which found concentrated stresses around the loaded implant (Guichet et al., 2002): the lower levels of strains found in the region between the implants for splinted crowns with the second molar present indicate the importance of splinting and the presence of a distal interproximal contact for optimizing load transfer.

Horizontal strains were found to be higher than shear strains in this study, agreeing with the results found using the finite element method (Hansson, 2000). The present results could therefore be used to validate the finite element models. Bone strength in compression is about 2.0–2.8 times the strength in shear (Reilly and Burstein, 1975). Consequently, the interfacial shear strain is suggested to be a critical parameter when considering implant failure and a high value of the interfacial shear strain implies an abrupt load transfer, which is considered to be unfavorable, whereas a moderate interfacial shear strain signifies a gradual load transfer into the bone (Hansson, 2000). Shear strains in the region between the first and second molar were found to be higher when the second molar was absent (Fig. 6A). The opposite occurred when the region between the implants was analyzed, with higher shear strains found when the molar was present (Fig. 6B). Splinting or not splinting the crowns had negligible effect on the shear strains.

Although implant failures can be related to unfavorable stress magnitudes, the physiologic tolerance thresholds of human jawbones for mechanical loading are not well known (Sahin et al., 2002). Non-splinted crowns were found to transmit higher strain levels to the supporting bone and this is particularly important when more unfavorable situations are considered, such as the case of low bone volume when short implants are used. One of the recommended methods to reduce the biomechanical stress to the bone–implant interface is to splint multiple implants together (Misch et al., 2006), which is supported by the results found in this study.

The epoxy modeling system used in this study has some limitations when predicting the response of biologic systems to applied loads—as with all modeling systems, including finite element analysis, mathematical models, or strain-gage studies (Akca et al., 2008). However, all of these systems can indicate, under carefully controlled conditions, where potential stress-related difficulties may arise (Akca et al., 2008; Jeong et al., 2003). Also, the elastic modulus of the cancellous bone simulant used in this study (PL-2, $E=210$ MPa) was of the same order of magnitude as that of cancellous bone ($E=490$ MPa). Therefore, mechanically, it was a good approximation to the actual material.

Using digital image correlation, splinted restorations were found to transfer lower horizontal strains to the supporting structures and exhibited better load sharing than non-splinted restorations, especially when a distal tooth to the restoration is absent. Strains were concentrated around the supporting structures and were more evident when non-splinted crowns were used to rehabilitate an edentulous space without a distal interproximal contact.

Shear strains were not affected by splinting or not splinting the crowns and the presence of the second molar was more...
effective in reducing shear strains in the regions between the molar.

**Conflict of interest statement**

None declared.

**Acknowledgements**

This investigation was supported by Research Grant No. 2007/06995-3 from São Paulo State Research Foundation (FAPESP) and by Research Grant No. 2450/09–7 from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Rodrigo Tiossi would like to thank the Minnesota Dental Research Center for Biomaterials and Biomechanics for hosting his visit and for providing the Digital Image Correlation equipment to support his study.

The authors wish to thank NEO DENT for supplying the implant components.

**References**


