Experimental and computational approach for the evaluation of the biomechanical effects of dental bridge misfit

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Abstract

Dental bridges supported by osseointegrated implants are commonly used to treat the partially or completely edentulous jaw. The bridges are manufactured in metal alloy using a sequence of technological steps which well match the requirement to get custom overstructures but does not guarantee geometrical and dimensional tolerances. Dentists often experience that a perfect fit of the bridge with the abutments is almost impossible to achieve. When a misfitting bridge is forced on the abutments, deformations may occur inducing a permanent preload at the fixture–bone interface and the greater the misfit the greater is the preload and the risk of implant failure. This work gives an evaluation of the biomechanical effects induced by a misfitting bridge when forced on two supporting dental implants. The strains induced in the bridge have been measured using two purposely designed and fabricated experimental devices allowing different types of misfit. FEM 3D models of the bridge and of the bridge anchored to the bone by implants have been developed. The former has been validated by simulating the same loading conditions as in the experimental tests and comparing the bridge strains. Both models have been used for the evaluation of the stress induced in the bridge and at the fixture–bone interface by bridge length errors. The results show that the method may help to estimate the stress distribution in the bridge and bone as a consequence of different dental bridge misfits. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The clinical treatment of partially or completely edentulous jaws has been significantly improved after the introduction of osseointegrated implants to support dental prostheses. The whole system includes two or more titanium dental implants (or fixtures) assembled with their abutments, which are used to fix the gold alloy bridge overstructure using various screws. The double-stage technique consists in the insertion of the fixtures in the mandibular or maxillary bone followed, after a waiting time ranging from four to six months during which the fixtures are osseointegrated according to the Brånemark technique, by the application of the abutments and the bridge (Adell et al., 1981; Albrektsson, 1988; Albrektsson and Sennerby, 1991). The bridge is manufactured in metal alloy using a sequence of technological steps: impression of the patient, preparation of the master model, waxing, casting, welding and ceramic processing. This technological process well matches the requirement to get a custom overstructure but does not guarantee geometrical and dimensional tolerances (Ma et al., 1997; Jemt, 1995, 1966; Lie and Jemt, 1994; Jemt and Lie, 1995).

In clinical practice, dentists often experience difficulties in screwing bridges to the supporting abutments. Such difficulties follow the geometrical and/or dimensional misfit of the bridge anchoring sites with respect to the relative positions of the supporting abutments. When a bridge is forced to be applied on the abutments, it undergoes a strain that causes a permanent preload at the fixture–bone interface (Jemt et al., 1991; Pietrabissa...
et al., 1998; Duyck et al., 1998; Clelland and van Putten, 1997). Due to the bone remodelling mechanism, the preload induced by the strained bridge may cause fixture movements toward the direction that produces the decrease of the bridge strain. The greater the bridge misfit, the greater is the bridge strain and hence the preload. Again, the greater the preload the greater is the risk that the fixture movement causes the implant failure (Jemt, 1991; Jemt et al., 1992; Van Steenberghe, 1989; Jemt and Book, 1996). Some efforts have been made to improve the fit between the bridge and the abutments by comparing different impression techniques to establish which one minimises the bridge misfit (Assif et al., 1996; Clelland and van Putten, 1997) and by preparing the bridge in a numerically controlled tooling machine, using stereophotogrammetry to measure the displacements (Strid, 1985). The latter method could be useful, but is not recommended as a standard procedure because of its complexity. The above considerations indicate the importance of evaluating the relationship between the bridge misfit and the bridge and bone preloads in order to minimise the risk of implant failure (Pietrabissa et al., 1998; Smedberg et al., 1996).

In this work, two purposely realised experimental devices have been used to measure the bridge strain induced by different types and sizes of bridge misfit. FEM 3D models of the bridge (Model 1) and of the bridge anchored to the bone by implants (Model 2) have been developed afterwards. Model 1 has been validated by simulating the same loading conditions of the experimental tests and comparing the bridge strains for length errors while Model 2 has not been validated. We have made the hypothesis that the validation of Model 1 may be sufficient for Model 2 also. Both Models 1 and 2 have been used for the evaluation of the stress induced in the bridge and at the fixture–bone interface by bridge length errors only.

The aim of this paper is to present a method able to evaluate the stresses at the fixture–bone interface due to dental bridge misfits and to test it for a specific bridge design. The results show that the method may help to estimate the stress distribution in the bridge and bone as a consequence of different dental bridge misfits. Further considerations on the effects of the stress distribution in the alveolar bone are beyond the limits of the present paper.

2. Materials and methods

The investigated bridge geometry is shown in Fig. 1. It is a bridge intended to be supported by two implants. Fig. 2 shows the two bridge-anchoring sites Cartesian systems (CSs) that, in case of perfect fit, correspond to those of the abutments. The bridge misfit may be represented as shifts or rotations of one of the two bridge CSs with respect to the corresponding abutment CS. Four misfits are possible (Figs. 2 and 3): shift in the X direction ($A_X$, called the bridge length error), shift in the Z direction ($A_Z$, called the bridge shear error), rotation around the X-axis ($\theta_X$, called the bridge torsion error) and rotation around the Y-axis ($\theta_Y$, called the bridge bending error).

Fig. 1. Geometry and dimensions (mm) of the investigated dental bridge. According to the chosen coordinate system, section A–A is contained in the ZX plane and section B–B in the symmetry plane perpendicular to the X-axis. In the top view, belonging to the XY plane, the thicker lines represent the edges where the boundary conditions have been applied.

Fig. 2. Cartesian systems (CSs) of the two bridge-anchoring sites corresponding, in case of perfect fit, to those of the two abutments. Considering the CS, as reference, the four possible misfits include shifts or rotations of the CS, as follows: bridge length error $A_X$, bridge shear error $A_Z$, bridge torsion error $\theta_X$ and bridge bending error $\theta_Y$. Two experimental devices have been designed and manufactured to allow the connection of the bridge with two implant systems located so as to have a misfit of desired type and value. The used implant system has been the Brånemark Standard Fixture SDCA 001 (3.75 × 10 mm) connected with the EsthetiCone Abutment (Nobel Biocare AB, Göteborg, Sweden). The first of
the two experimental devices consists of a framework (Fig. 4a) with two slides that can be translated using two micrometer screws, 0.5 mm pitch. Each slide supports one abutment. One slide enables to set bridge length errors $A_X$, the other to set bridge shear errors $A_Z$. The second experimental device consists of a framework (Fig. 4d) with two shafts that can be rotated. Each shaft supports one abutment. One shaft enables to set bridge torsion errors $\theta_X$, the other to set bridge bending errors $\theta_Y$.

Several bridges have been fabricated, using the wax casting technique, in V CLASSIC gold alloy (Metaux Precieux SA Metoral, Neuchatel, Switzerland) having the following composition in weight: 75% Au, 19% Pd, 1% Ag and 2% In. The bridges have been equipped on their upper surface with two strain gauges to measure the bridge deformation induced by the misfit. The adopted strain gauges are LY13-06/120 (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) with 6 mm reference length in the measurement direction and 120Ω reference resistance. Both the strain gauges have been glued parallel to the bridge $X$-axis in case of $A_X$ (Fig. 4b) or $A_Z$ (Fig. 4c) error, one parallel to the bridge $X$-axis and the other rotated by 45° in case of $\theta_X$ (Fig. 4e) or $\theta_Y$ (Fig. 4f) error. Reference lines have been marked on the top of the bridge in order to obtain a proper alignment of the strain gauges.

The bridge has been mounted on the shift error device and the slides have been translated to obtain the minimum bridge strain on the basis of the strain gauge measurement. This relative position of the slides, and hence of the abutments, has been the reference position corresponding to no shift error. Then the bridge has been removed from the abutments. Using one of the two micrometer screws it has been possible to translate one slide and set the desired shift error. The bridge has been mounted again on the abutments with the strain gauges to measure the bridge strain due to the set error as $e_{A_X} = (e_{X1} + e_{X2})/2$ for $A_X$ and $e_{A_Z} = (e_{X2} - e_{X1})/2$ for $A_Z$ where $e_{X1}$ and $e_{X2}$ are the measured strains (Figs. 4b and c). The bridge has been removed again, a new error has been set and the procedure has been repeated several times using slide shift steps of 10 μm for a maximum error of 0.1 mm. Both length and shear bridge errors have been separately investigated.

The same procedure has been adopted for the rotation error framework where the shaft rotation step is 1° and the maximum depends on the feasibility of mounting the bridge on the rotated abutments. The bridge strain is $e_{A_X} = e_{A_5}$ for $\theta_X$ and $e_{A_Y} = e_{X}$ for $\theta_Y$ where $e_{A_5}$ and $e_{X}$ are the strains measured by the strain gauge rotated by 45° with respect to the bridge $X$-axis and parallel to the bridge $X$-axis, respectively (Figs. 4e and f).

### 2.2. Computational procedure

Two FEM models have been developed to investigate the stress induced in the bridge and at the fixture–bone interface by bridge length errors only. The former is a 3D model of half a bridge mounted on its abutment (Model 1). Only half a bridge has been considered as the system shows a geometrical and mechanical symmetry plane. Model 1 is shown in Fig. 5a and consists of 8288 eight-node hexahedrons for a total of 10,519 nodes. The definitive mesh has been obtained after subsequent grid refining in order to obtain grid-independent results.

With regard to the boundary conditions of Model 1, no displacement in the $X$ direction has been imposed at the nodes lying along the symmetry plane of the bridge. The bridge length error between the abutment and the
bridge has been imposed at the gold screw-bridge surface by sequential steps of displacement in the $X$ direction. Loading conditions consist of five steps of displacement and, due to the fact that Model 1 represents only half a bridge, each step corresponds to one half of the displacement applied during the experimental tests. This procedure has been adopted to validate Model 1 by comparing experimental data with the strains values calculated on the upper surface of the bridge at the same bridge length error. The second 3D model (Model 2) consists of half a bridge (Model 1) connected by a gold screw to the titanium abutment which, in turn, is connected by a titanium screw to the fixture inserted in a segment of cortical bone. The implant, the abutment and the titanium screw have been assumed to be a continuous structure and the thread of the screws has not been considered. It has also been assumed that the osseointegration at the bone–implant interface has been completely achieved. Model 2 is shown in Fig. 5b and consists of 19,776 eight-node hexahedrons for a total of 22,998 nodes.

The presence of the bone in Model 2 produces a compliant constraint to the fixture and hence the bridge length error causes a deformation both in the bridge and in the bone. This occurrence reduces the strain in the bridge in comparison with both the experimental situation and Model 1. The boundary conditions applied to the bridge of Model 2 have been the same as those already used for Model 1. As regards the bone segment, on the edge contained in the symmetry plane no displacement in the $X$ direction has been applied to respect the symmetry constraint while the nodes on the other side have been considered as fixed joints, assuming that the mandibular bone is capable of avoiding the bone segment movements. The loading conditions have been displacement steps, corresponding to different bridge length errors, applied to the symmetry surface of the bridge.

All materials in both models have been assumed to be homogeneous, isotropic and linear elastic. Table 1 shows the mechanical properties assumed for the different materials. In particular, V CLASSIC gold alloy properties have been obtained from experimental tests.

Model 1 has been developed to evaluate the reliability of the numerical simulation. The experimental results have been used to validate the model by comparing the strains measured with those calculated. We have made the hypothesis that the validation of Model 1 may be transferred to Model 2, at least with reference to the bridge. Model 2 has been adopted to evaluate the stress distribution at the fixture–bone interface where no experimental test can be performed.

The pre/post data processing program MSC/PATRAN has been used to generate the geometry and the mesh of the two models while the analyses have been performed using the ABAQUS code.

3. Results

Fig. 6 reports the measured strains corresponding to different types and values of bridge misfit. The panels referring to $A_X$ and $A_Z$ report the measured strains for errors corresponding to 20 $\mu$m steps. For all the bridge misfit types, the measured strain increases with the error. In particular, for the maximum considered bridge length error $A_X = 100$ $\mu$m, the measured local bridge strain has
Fig. 6. Bridge strains measured during experimental tests: (a) strains induced by bridge length error $\varepsilon_{AX} = (\varepsilon_{X2} + \varepsilon_{X1})/2$; (b) strains induced by bridge shear error $\varepsilon_{AZ} = (\varepsilon_{X2} - \varepsilon_{X1})/2$; (c) strains induced by bridge bending error ($\varepsilon_{A_h} = \varepsilon_{X}$); (d) strain induced by bridge torsion error ($\varepsilon_{A_t} = \varepsilon_{45}$).

been about 200 $\mu$m/m while for the same value of maximum considered bridge shear error $A_Z = 100 \mu$m, the measured local strain has been about 65 $\mu$m/m.

As regards Model 1 simulations, we have calculated the mean strain at the upper surface of the bridge in the region corresponding to that of the actual bridge where one of the two strain gauges has been glued (Fig. 5a). One should note that the measured and calculated strain (about 200 $\mu$m/m) for the maximum bridge length error ($A_X = 100 \mu$m) is lower than the strain (5000 $\mu$m/m) induced in a 20 mm beam stretched by 100 $\mu$m. This depends on the shape of the bridge and on the applied boundary conditions (Fig. 1) that produce both tensile and bending stress pattern in the bridge.

Table 2 reports the comparison between the measured ($\varepsilon_{AX}$) and calculated ($\varepsilon_{AX_n}$) strains for five bridge length errors. The percentage error $((\varepsilon_{AX} - \varepsilon_{AX_n})/\varepsilon_{AX_n}) \times 100$ is also reported indicating that Model 1 reproduces the experimental results with a small underestimation (maximum about $-10\%$).

Fig. 7 shows the von Mises stress distribution on the surface of Models 1 and 2 for bridge length error $A_X = 100 \mu$m. The most stressed region of the bridge has been that close to the connection between the gold cylinders and the connecting beam, where the cross section is the smallest one. The stress pattern has higher values for the bridge of Model 1 in comparison with that of the bridge of Model 2 and this is in agreement with the more compliant constraint due to the bone segment in Model 2. Fig. 7 also shows a stressed region in the bone near the fixture–bone interface.

Table 2

<table>
<thead>
<tr>
<th>$A_X$ (\mu m)</th>
<th>$\varepsilon_{AX}$ (\mu m/m)</th>
<th>$\varepsilon_{AX_n}$ (\mu m/m)</th>
<th>$((\varepsilon_{AX} - \varepsilon_{AX_n})/\varepsilon_{AX_n}) \times 100$ (%)</th>
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<td>160</td>
<td>164</td>
<td>-2.4</td>
</tr>
<tr>
<td>100</td>
<td>202</td>
<td>203</td>
<td>-0.5</td>
</tr>
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Fig. 8 shows local normal stresses, local axial shear stresses and local circumferential shear stresses in a small annulus around the fixture–bone interface for bridge length error $A_X = 100 \mu$m. Local stress means a stress referred to each element local coordinate system. Local normal stresses give information on the compression and tension (the tension is achieved if the fixture–bone osseointegration allows it, as in our hypothesis) produced in the bone that could be responsible for the bone remodelling process. Local shear stresses may account for the failure of the fixture–bone mechanical interface.
Fig. 7. (a) Model 1 and (b) Model 2 von Mises stress distributions calculated for bridge length error $A_x = 100\,\mu m$.

Fig. 8. Local normal stress, local axial shear stress and local circumferential shear stress calculated for a bone annulus around the fixture. The bridge length error is $A_x = 100\,\mu m$. Local stress means a stress calculated with reference to each element coordinate system.

4. Discussion

The present work faces the problem of the biomechanical effects induced by the misfit between a dental bridge and its supporting implants. This problem is well known to dentists and has a clinical relevance as the application of a misfitting bridge generates a preload both in the bridge-implant structure and in the bone around implants (Jemt et al., 1991, 1992; Smedberg et al., 1996). Usually, the bridge preload is not large enough to increase significantly the normal stress that cyclically loads the bridge-implant structure during chewing, speaking and other normal activities. Hence, the risk of bridge-implant structure failure is not the main risk due to the preload. The main preload pitfall is the increasing of the bone stress that may produce bone microfractures at the fixture–bone interface and/or, more frequently, a bone remodelling process that may cause the osseointegration loosening and the clinical failure of one or more components requiring the prosthesis removal.

Some studies have been published with the aim to suggest solutions to avoid the misfitting bridge outcome (Strid, 1985; Assif et al., 1996) or to evaluate it (Jemt, 1996). The former propose new technological processes either to fabricate the bridges, which usually increases the prosthetic cost significantly, or to promote the use of cemented abutments that should better compensate the bridge misfits. Our study is not intended to give a solution to avoid the bridge misfit, but it proposes a reliable method that may be of help in evaluating new bridge-producing technologies such as new connecting systems.

We have utilised both an experimental and a computational approach to evaluate the biomechanical effects of bridge misfits. The adopted procedure allows measuring the bridge strains due to each type of dimensional or geometrical bridge misfit. At present, the tests have been carried out using a bridge supported by two implants and adopting the Bränemark system. The results could be significantly dependent on the bridge geometry and on the type of adopted implant system. The use of a bridge supported by a greater number of implants, or by both implants and natural teeth, introduces a greater number of possible error types and is beyond the purposes of the present investigation. The main limitation of the experimental procedure is that the shift error device is unable to compensate bridge rotation errors (the two abutments are always parallel to each other) and the rotation error device is unable to compensate bridge shift errors (the distance between the two abutments is constant). Usually, a bridge is simultaneously affected by all the types of error and when mounted on one of the two error devices all the errors cannot be eliminated by moving the slides or the shafts. This effect is clearly indicated by the bridge bending error experimental results (Fig. 6) where $\theta_y = 0^\circ$ leads to $\epsilon_y \approx 25\,\mu m$.

As Model 1 has displayed strains close to those measured on the actual bridge, we have considered the bridge model as validated. Model 2, on the contrary, presents some limitations mainly related to the geometry and the mechanical properties adopted for the bone segment. As a consequence the stresses calculated with Model 2 should be considered only as approximate. It may be interesting to underline that, as expected, the presence of the bone decreases the stress values with respect to the gold cylinder fixed constraints adopted in Model 1 to
simulate the boundary conditions of the experimental tests.

In conclusion, the adopted experimental/computational procedure seems to be feasible to evaluate the biomechanical effects induced by dental bridge misfits in terms of both bridge and bone preloads. At present, only length errors have been considered in the numerical simulations. One should consider that, except for the bending errors, the other error types do not show a mechanical symmetry plane and hence a complete bridge model is required. Further investigations will need a larger model involving the four error types, more bridge shapes, different implant systems with respect to the bridge-abutment connection and a more proper model of the bone mechanical properties.

References


