Biomechanical testing of zirconium dioxide osteosynthesis system for Le Fort I advancement osteotomy fixation

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ARTICLE INFO

Keywords:
Maxillofacial surgery
Patient specific implants
Zirconium dioxide
Osteosynthesis system

ABSTRACT

The following work is the first evaluating the applicability of 3D printed zirconium dioxide ceramic miniplates and screws to stabilize maxillary segments following a Le-Fort I advancement surgery. Conventionally used titanium and individual fabricated zirconium dioxide miniplates were biomechanically tested and compared under an occlusal load of 120 N and 500 N using 3D finite element analysis. The overall model consisted of 295,477 elements. Under an occlusal load of 500 N a safety factor before plastic deformation respectively crack of 2.13 for zirconium dioxide and 4.51 for titanium miniplates has been calculated.

From a biomechanical point of view 3D printed ZrO\textsubscript{2} mini-plates and screws are suggested to constitute an appropriate patient specific and metal-free solution for maxillary stabilization after Le Fort I osteotomy.

1. Introduction

Le Fort I osteotomy is a well-established surgical technique to correct midfacial deformities presenting the clinical picture of unpleasant aesthetic facial contour, facial asymmetries or malocclusion. The surgical treatment includes the separation of the maxilla into free segments to enable its repositioning in the desired, pre-surgically planned position. Regarding the fixation of the adjusted segments, the use of titanium mini-plates and screws is referred as the gold standard (Coskunses et al., 2015; He et al., 2015; Pan and Patil, 2014; Ueki et al., 2006).

Typically, the maxillary segment position is planned and primarily reconstructed with articulated dental models made from plaster casts before surgery. As osteotomies are conventionally based on two-dimensional (2D) lateral teleradiographies the precise intraoperative adjustment of the segments using surgical splints is often challenging. To overcome this issue alternative treatment approaches have been introduced. Preoperative virtual surgery planning and rapid prototyping surgical guides have been applied to ensure three-dimensional (3D) planning and separation of the segments in the exact position (He et al., 2015; Hirsch et al., 2009; Li et al., 2013; Mazzoni et al., 2015; Philippe, 2013). However, commercial straight titanium mini-plates, used for fixation still demand contouring to fit segmental maxillary geometry profiles for each individual patient, encountering a risk of inaccurate re-fixation of the segments (He et al., 2015). Furthermore, contouring of the titanium plates often comes along with repeated bending leading to less stress resistance of the plate, increasing the risk of fatigue failure (Philippe, 2013). Custom made prefabricated titanium mini-plates have been investigated and discussed to allow precise control of the surgical procedure and decrease operative time (Mazzoni et al., 2015; Philippe, 2013). Beside titanium plates, poly-L-lactic acid plates and wires have been successfully used to achieve adequate postoperative maxillary stability (Egbert et al., 1995; Ueki et al., 2012). However, metal free solutions are not frequently used, titanium remains the material of choice though its removal is often indicated due to unclear potential bioactive corrosive products (Bianco et al., 1996; Stejskal and Stejskal, 1999; Weingart et al., 1994). Although zirconia or zirconium dioxide ceramic (ZrO\textsubscript{2}) gained increasing popularity in the field of oral implantology its use as an osteosynthesis systems has not yet been described (Kubasiewicz-Ross et al., 2017; Manicone et al., 2007). The fact that ZrO\textsubscript{2} wear particles induced less pro-inflammatory gene expression compared to titanium particles is considered one rationale for its use (Obando-Pereida et al., 2014). Furthermore, ceramic-based miniplates are identified to cause less artifacts in magnetic resonance imaging (MRI) or computer tomography (CT) compared to titanium (Neumann et al., 2006). Although ZrO\textsubscript{2} is not resorbable its removal would fulfill the request for a bioinert and metal-free osteosynthesis system in maxillofacial surgery (Hayashi et al., 1992; Kubasiewicz-Ross et al., 2017).

The applicability of ZrO\textsubscript{2} osteosynthesis system to stabilize maxillary segments following a Le-Fort I advancement surgery has not yet been...
been evaluated. ZrO₂ belongs to the materials with the highest strengths suitable for medical use (von Wilmowsky et al., 2014). The aim of this study is to test if individual ZrO₂ mini-plates can stand occlusal forces and might constitute an appropriate solution for maxillary stabilization after Le Fort I osteotomy. Postoperative biomechanical behavior and stress distribution on titanium versus ZrO₂ mini-plates after Le Fort I advancement surgery was evaluated using 3D finite element analysis (FEA).

2. Materials and methods

Using two cast blocks, reflecting the separated maxillary segments stabilized in the desired position using virtually planned and individual fabricated ZrO₂ mini-plates.

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Poisson ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>14.8</td>
<td>0.3</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>210</td>
<td>0.3</td>
</tr>
<tr>
<td>Titanium</td>
<td>144</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Part</th>
<th>No. of elements</th>
<th>No. of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>113,739</td>
<td>161,428</td>
</tr>
<tr>
<td>4 hole miniplate</td>
<td>5760</td>
<td>7884</td>
</tr>
<tr>
<td>3 hole miniplate</td>
<td>9725</td>
<td>13,152</td>
</tr>
<tr>
<td>Screw</td>
<td>4873</td>
<td>3132</td>
</tr>
<tr>
<td>Overall model</td>
<td>295,477</td>
<td>420,939</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Material</th>
<th>$P_{\text{max}}$ stress (MPa)</th>
<th>Max. Von Mises stress (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Safety factor before plastic deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>ZrO₂</td>
<td>41.09</td>
<td>47.75</td>
<td>390</td>
<td>8.16</td>
</tr>
<tr>
<td>120</td>
<td>Titanium</td>
<td>35.18</td>
<td>47.87</td>
<td>828</td>
<td>17.29</td>
</tr>
<tr>
<td>500</td>
<td>ZrO₂</td>
<td>72.83</td>
<td>182.82</td>
<td>390</td>
<td>2.13</td>
</tr>
<tr>
<td>500</td>
<td>Titanium</td>
<td>60.53</td>
<td>183.32</td>
<td>828</td>
<td>4.51</td>
</tr>
</tbody>
</table>

Fig. 1. The experimental set up showing the two cast blocks, reflecting the separated maxillary segments stabilized in the desired position using virtually planned and individual fabricated ZrO₂ mini-plates.

Fig. 2. Black arrows on the generated FEA model indicate the direction of loads (120 N, 500 N) simulating occlusal forces.
Values for ZrO\textsubscript{2} were obtained from Lithoz, Austria and that of pure titanium grade IV as well as that of bone were adopted from the literature (Ataç et al., 2008). Titanium has a pronounced yield behavior whereas ZrO\textsubscript{2} is a brittle material hardly allowing plastic deformation. Therefore, the maximum allowable value for Von Mises stress of ZrO\textsubscript{2} was set according to the yield strength value listed in Table 3. The number of elements and nodes identical for both models are listed in Table 2. The plate-to-screw, plate-to-bone and screw-to-bone interface assumed a full bonded condition to exclude micro-movements and to allow stress transfer continuity. The boundary conditions of screw – plate, plate-mono-cortical, and screw-mono-cortical fixation were created as hard contact surface condition. 120 N, 500 N were applied vertically in the molar and premolar region (Fig. 2).

Abaqus CAE 6.12\textsuperscript{®} standard/implicit finite element solver served to analyze the FE models and Abaqus CAE 6.12\textsuperscript{®} visualizer was used for visualizing the resulted stress concentrations.

3. Results

The 3D-FEA method was used to assess the Von Mises stress as well as the principal maximum stress ($P_{\text{max}}$) on zir ZrO\textsubscript{2} and titanium miniplates in the Le Fort I advancement model. The maximum values of $P_{\text{max}}$ and Von Mises stress of the miniplates under 120 N and 500 N vertical loading conditions are shown in Table 3 for model I (titanium) and II (ZrO\textsubscript{2}).

All stress values are given in MPa (Newton per millimeter square). A color scale with 13 stress values served to evaluate quantitatively the stress distribution in the plates, screws and the adjacent bone tissue and to provide clear visualization of the stress concentrations.

3.1. Von Mises stress values in model I (titanium)

The resulted Von Mises stresses in the titanium miniplates under 500 N loading condition are shown in Fig. 3a. Maximum Von Mises Stress was 47.87 MPa (120 N) (Fig. 4a) and 183.32 MPa (500 N) respectively.

3.2. Von Mises stress values in model II (ZrO\textsubscript{2})

The simulation results indicate that the maximum von Mises stresses for the ZrO\textsubscript{2} miniplates were 47.75 MPa under 120 N and 182.82 MPa under 500 N vertical load. Fig. 3b illustrates the location of Von Mises stresses of the ZrO\textsubscript{2} miniplates at 500 N.

In both models highest von Mises stresses were determined at the bending of the anterior placed plates. $P_{\text{max}}$ for the ZrO\textsubscript{2} plates was 41.09 MPa under weak (120 N) and 72.83 MPa under heavy loads (500 N), respectively. Titanium miniplates resulted in $P_{\text{max}}$ levels of 35.18 MPa for 120 N and 60.53 MPa for 500 N loaded models.

The safety factor before plastic deformation at titanium and crack at ZrO\textsubscript{2} occurs was 2.13 for ZrO\textsubscript{2} and 4.51 for titanium miniplates under a occlusal load of 500 N. When 120 N were applied, calculations revealed a safety factor of 8.16 for ZrO\textsubscript{2} and 17.29 for titanium (Figs. 4b and 5b).

4. Discussion

The present study evaluates the applicability of a 3D printed ZrO\textsubscript{2} osteosynthesis system to stabilize maxillary segments following a Le Fort I advancement surgery. Results reveal a safety factor before plastic deformation respectively crack of 2.13 for ZrO\textsubscript{2} and 4.51 for titanium miniplates under an occlusal load of 500 N. Although no data regarding the bite force after Le Fort I Osteotomy exist, Harada et al. reported mean bite forces of 66.5 N after 2 weeks, 128.8 N after 4 weeks and 301.5 N after 6 months following BSSO surgery. Thus, occlusal loads of 120 N and 500 N were considered to simulate realistic bite forces during and after the bone healing phase of maxillary segments (Harada.
et al., 2000). Multiple studies report various options, including titanium plates, poly-L-lactic acid plates and wires to achieve satisfactory maxillary stability after single-piece maxillary impactions and/or advancements. All methods provided satisfactory results without any appreciable differences (Egbert et al., 1995; Frofitt et al., 1996, 1991; Skoczylas et al., 1988; Ueki et al., 2012). However, the 4-titanium plate fixation technique constituted the gold standard as compared to the 2-plate fixation technique it significantly reduces stress on healing bones (Ataç et al., 2008). The usage of ZrO2 devices has not yet been described.

Within the limitations of the study, a safety factor of 2.13 for the ZrO2 miniplates under excessive occlusal load is considered adequate to ensure an uneventful clinical usage.

It is to be noted that to achieve comparable results, the evaluated ZrO2 miniplates were fabricated according to the design and dimensions of conventionally available titanium miniplates used for model I without any pre-optimization. Thus, modifications of design and structure to even improve biomechanical behavior especially fracture resistance are clearly seen as new assignments for further investigations.

Titanium has been the gold standard for decades and still remains the material of choice for rigid fixation of freed maxillary segments (Coskunses et al., 2015; Philippe, 2013). Nevertheless, higher concentrations of titanium have been detected within tissue attached to implant surfaces and regional lymph nodes (Bianco et al., 1996; Weingart et al., 1994). These findings raise the question if titanium or its corrosive products have an impact on patients’ individual health (Stejskal and Stejskal, 1999; Valentine-Thon and Schiwara, 2003). Although this issue is not fully elucidated, metal free solutions are not routinely used. Zirconium ceramic has shown excellent biocompatibility and tissue integration (Manicone et al., 2007). Concerning dental implants the low affinity of zirconia to bacteria come along with adequate osseointegration of the material (Al-Radha et al., 2012; von Wilmowsky et al., 2014).

Following the results of this study, ZrO2 is considered as a potential solution to the raising claim of patients to stable, metal-free and bioinert osteosynthesis material without the routine need of removal (Pan and Patil, 2014; Verweij et al., 2016). Another crucial advantage of a ZrO2 compared to a titanium osteosynthesis-system is that it does not cause artifacts in the CT or MRI scans (Neumann et al., 2006). This allows proper radiologic assessment of tissue adjacent to the osteosynthesis material and therefore unrestricted detection of diseases is possible (Neumann et al., 2006). Furthermore, patient specific fabricated osteosynthesis and the use of surgical cutting templates is considered to allow a precise positioning of the segments in the virtually planned position (He et al., 2015; Philippe, 2013).

Although clinical trials are missing, the findings of this study assume that individual ZrO2 osteosynthesis screws and plates are suitable to stabilize freed maxillary segments after Le-Fort I advancement osteotomy. Further, a variety of possible indications for the use of ZrO2 osteosynthesis material, especially in the field of facial traumatology, is considered. Nevertheless, ZrO2 has gained increasing popularity as an implant material. Not only the fact that patients assert the claim to best esthetic results and with increasing frequency to metal-free solutions but also the bioinert property, especially when coated with saliva are reasons for its utilization.

However, increased fracture risk compared to titanium implants due to low fracture toughness and stress shielding as a result of a very high
elastic modulus (210 GPa) compared to cancellous bone (14.8 GPa) are drawbacks of ceramics (von Wilmowsky et al., 2014). Furthermore, precise preoperative planning of the desired position of segments is essential as individual ZrO₂ implants would not allow any intraoperative adjustments compared to conventional titanium miniplates (Araújo et al., 2015; He et al., 2015; Hirsch et al., 2009).

As this study evaluates the biomechanical behavior of a ZrO₂ osteosynthesis system in the stabilization of the maxillary segments following Le-Fort I osteotomy for the first time, it has to be considered as a thought-provoking impulse to establish metal-free solutions. Following the results, this study can be considered as a pioneer work to introduce a new material (ZrO₂) for individually patient specific designed 3D printed implants in maxillofacial surgery. Beyond a doubt the not realistic simulation of the maxillary segments and the load only applied in one direction do not properly represent the dynamic loading during function. In addition, bone was modeled as linearly elastic and homogenous even though bone in reality is anisotropic and inhomogeneous.

For clinical usage advance computational work is necessary to allow precise fabrication of individual ZrO₂ osteosynthesis parts and the surgical templates to ensure a predictable osteotomy of the segments. Nevertheless, the reported findings indicate a possible scope of patient specific fabricated metal-free osteosynthesis systems.

Conflict of interest and source of funding

The authors do not have any financial interests, either directly or indirectly, in the products or information listed in the paper.

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