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

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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_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 esthetic 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_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_2 wear particles induced less pro-inflammatory gene expression compared to titanium particles is considered one rationale for its use (Obando-Pereda 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_2 is not resorbable its 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_2 osteosynthesis system to stabilize maxillary segments following a Le-Fort I advancement surgery has not yet

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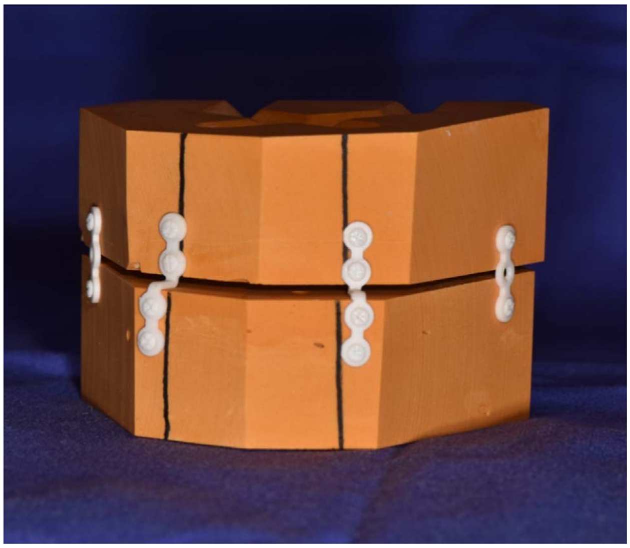

Fig. 1. The experimental set up showing the two cast blocks, reflecting the separated maxillary segments stabilized in the desired position using virtually planned and individual fabricated ZrO_2 mini-plates.

Table 1
Mechanical properties of cortical bone, ZrO_2 and titanium in finite element analysis.

Material	Young's modulus (ε) GPa	Poisson ratio (ν)
Cortical bone	14.8	0.3
ZrO_2	210	0.3
Titanium	144	0.33

Table 2
Number of elements and nodes for different structures and the overall model.

Part	No. of elements	No. of nodes
Bone	113,739	161,428
4 hole miniplate	5760	7884
3 hole miniplate	9725	13,152
Screw	4873	3132
Overall model	295,477	420,939

Table 3
Maximum Von Mises stress, P_{max} stress, yield strength and safety factor before plastic deformation under different loads for titanium and zirconium dioxide miniplates.

Load (N)	Material	P_{max} stress (MPa)	Max. Von Mises stress (MPa)	Yield strength (MPa)	Safety factor before plastic deformation
120	ZrO_2	41.09	47.75	390	8.16
120	Titanium	35.18	47.87	828	17.29
500	ZrO_2	72.83	182.82	390	2.13
500	Titanium	60.53	183.32	828	4.51

been evaluated. ZrO_2 belongs to the materials with the highest strengths suitable for medical use (von Wilmowsky et al., 2014). The aim of this study is it to test if individual ZrO_2 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 ZrO_2 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 segments of the maxilla, advancement of 5 mm and an extrusion of 2 mm was constructed. Individual fabricated ZrO_2 mini-plates and screws (Lithoz®, Vienna, Austria) were applied to stabilize the cast blocks in its position (Fig. 1). Two straight 3-hole and two angled 4-hole ZrO_2 mini-plates, secured with twelve cylindrical ZrO_2 screws all of which identical to the dimensions of the conventionally available titanium osteosynthesis system Modus 2.0 of Medartis®, Basel, Switzerland were used to achieve a stable fixation. Following this, 3D imaging of the cast blocks using a micro-CT computer tomography (RayScan 250E, Meersburg, Germany) with a voxel size of 65 µm was performed. The resulting DICOM data sets were then transferred to a stereolithography file format using VG Studio MAX 3.0 (Volume Graphics, Heidelberg, Germany). Abaqus CAE 6.12® software was used for creating 3D FE models of the ZrO_2 and titanium mini-plates, the cast blocks and the screws. All material properties including cortical bone were assumed to be isotropic, homogeneous and linear elastic. In Model I plates and screws were simulated to be made of conventional pure titanium grade IV and in model II of the existent printed ZrO_2. Material property assumptions regarding Young's modulus and Poisson ratios are listed in Table 1.

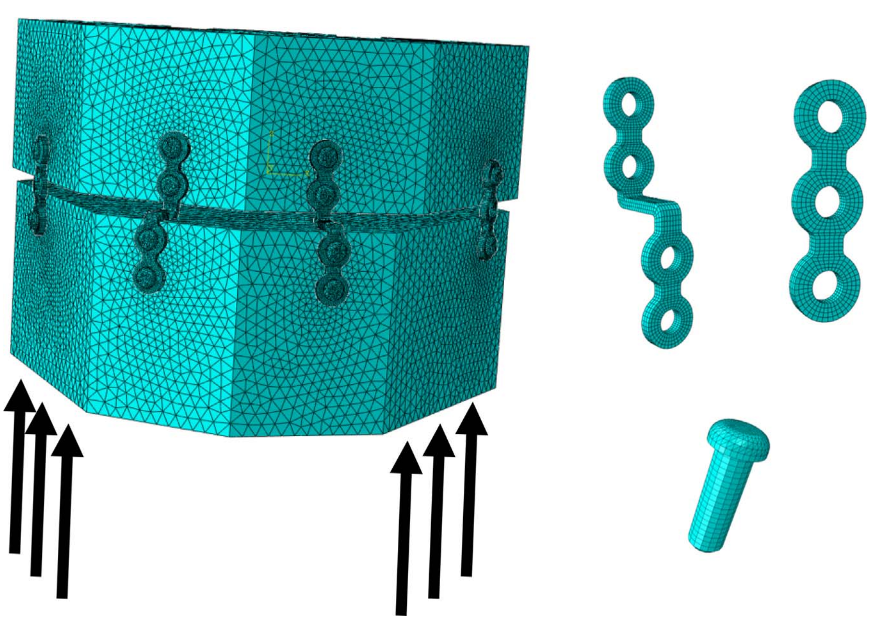

Fig. 2. Black arrows on the generated FEA model indicate the direction of loads (120 N, 500 N) simulating occlusal forces.