1. Introduction

Fractures of the orbital floor are a common result of orbital injury. These fractures can vary in size from a small crack to large defects. Fractures of the orbital floor mainly occur medial to the infraorbital groove and canal and medio caudal from the orbital roof, due to the limited thickness of the bone in this area (Metzger et al., 2007).

As a result of an orbital floor fracture, the volume of the orbit can increase with hypoglobus, enophthalmos and diplopia as well known consequences. Hence a most important asset in the treatment is the anatomical reconstruction of the orbital wall thereby restoring the pre-existent volume. To achieve an anatomical reconstruction a wide variety of materials has been used, ranging from autologous bone grafts to non-resorbable and resorbable alloplastic implants like e.g., titanium, polyethylene, silicone, and polylactic and -glycolic acid (Potter and Ellis, 2004). These materials differ with respect to their mechanical properties and therefore in their behaviour under pressure load. When deformation (sagging) of materials and subsequent increase of orbital volume occurs complications, like enophthalmos, may arise. There are 4 important variables that influence the deformation of a reconstruction material: (1) the size of the orbital floor defect, (2) the mechanical properties of the used reconstruction material, (3) the thickness of the reconstruction material and (4) the pressure load of the orbital content on the reconstruction material. Thus to decide (pre-operative) which reconstruction material could be (most) suitable for reconstruction of an orbital floor defect, all 4 mentioned variables should be taken into account.

Previously, efforts have been made to relate the choice of reconstruction material to size and extent of orbital floor defects. Furthermore, the relation between increase of the orbital cavity volume following an orbital floor fracture and enophthalmos has been subject of investigation (Ahn et al., 2008; Cunningham et al., 2005; Hwang and Kim, 2010; Jaquiery et al., 2007; Ploder et al., 2002). Al-Sukhun et al. even developed a three dimensional finite-element model of the human orbit, to predict orbital deformation following blunt trauma (Al-Sukhun et al., 2006).

However, to our knowledge none of the publications on this topic considered the relation between defect size, mechanical
properties and thickness of reconstruction materials on one hand and deformation of the reconstruction material leading to enophthalmos on the other. Therefore, we developed a mathematical engineering model of the orbital floor in which materials for orbital floor reconstruction can be evaluated in order to formulate recommendations for the choice of the most suitable implant material in orbital floor reconstruction in relation to defect size. When applying this model, a surgeon is able to decide on which material(s) are suitable for reconstruction of the defect in the orbital floor taking the relation between material properties and defects size into account.

2. Materials and methods

2.1. Mathematical engineering model

Based on the models and equations of the ‘classical plate equation’ described by Roarks et al., the deformation or sagging of reconstruction materials can be calculated using a simplified model (Fig. 1). By assuming the implant materials and the orbital floor defects to be circular and assuming that the circular reconstruction material is freely supported along its periphery (i.e., not fixed to the edges of the fractured orbital floor) and that the load is homogeneously distributed, the deformation can be calculated according to (Young, 1989):

$$\frac{p r^4}{E t^4} = 1.016 \frac{h}{1 - v^2} + 0.376 \left( \frac{h}{r} \right)^3$$  \hspace{1cm} (1)

In this equation:
- $h =$ deformation of the disk-shaped implant at its center (m)
- $p =$ applied load (Pa)
- $r =$ radius of the defect of the orbital floor (m)
- $v =$ Poisson’s ratio of the material from which the implant is prepared (assumed to be 0.3).
- $t =$ thickness of the implant (m)
- $E =$ flexural modulus of the material from which the implant is prepared (Pa)

(Note that the modulus determined in bending experiments is the flexural modulus, while when determined in tensile tests it is referred to as the Young’s modulus or tensile modulus. At small deformations, however, these values are quite similar.)

This equation accounts for the 4 important variables mentioned in the introduction which influence the deformation of reconstruction materials, i.e., size of orbital floor defect, pressure load on the implant material, mechanical properties and thickness of implant materials. The assigned values for these variables are below elucidated. To characterize the size of the orbital floor defects we used the classification of Jaquiéry et al. (Jaquiéry et al., 2007). This classification groups the orbital floor fractures and defects according to their size and the involvement of certain anatomical landmarks. An overview is presented in Table 1. In this scheme, the defect size of the orbital floor increases in categories 1 through 4. Category 5 defects are relatively large defects that also involve the orbital roof. In our study categories 1–4 corresponded to 1, 2.5, 4, 5.5 cm², respectively, based on the evaluations of the orbital floor by Ploder et al. (Ploder et al., 2002). The radius ($r$) of the defect was adjusted accordingly, although it should be noted that by changing the radius of the defect in the equation a virtually infinite number of defect sizes can be evaluated.

Based on the research by Cordewener et al. it was assumed that the pressure load ($p$) on the orbital floor implant due to the load of the orbital content after trauma was about 13 mmHg (1.73 kPa) (Cordewener et al., 1995). This assumption is based on the fact that the normal retrobulbar pressure (RBP) in humans ranges from 3 to 4.5 mmHg. This pressure can increase by approximately 2 mmHg due to functional eye movements (Moses et al., 1982, 1984; Simonsz et al., 1985). Analogous to Cordewener et al. we decided that a pressure load corresponding to twice the RBP taking

![Fig. 1. Technical illustration of a model in which the deformation ($y_e - h$) of the reconstruction materials can be evaluated (top view and lateral view). Note that here the reconstruction material is freely supported (this is indicated by the dotted line shown in the axial view of the model). $'p'$ = applied pressure/pressure load; $'h'$ = deformation of reconstruction material; $'r'$ = radius of orbital floor defect radius.](image)

<table>
<thead>
<tr>
<th>Defect category</th>
<th>Schematic frontal view of the orbital floor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>Isolated defect of the orbital floor, 1–2 cm² in size</td>
<td></td>
</tr>
<tr>
<td>Category 2</td>
<td>Defect of the orbital floor, larger than 2 cm²</td>
<td></td>
</tr>
<tr>
<td>Category 3</td>
<td>Defect of the orbital floor, larger than 2 cm² with lateral extension into the infraorbital fissure</td>
<td></td>
</tr>
<tr>
<td>Category 4</td>
<td>Defect of the entire orbital floor extending into medial wall, &gt;4 cm² in size</td>
<td></td>
</tr>
<tr>
<td>Category 5</td>
<td>Defect of the entire orbital floor, &gt;4 cm² in size extending into the orbital roof</td>
<td></td>
</tr>
</tbody>
</table>
normal eye function into account, thus 13 mmHg, could be a reasonable representation of the pressure load subjected to implant materials after trauma.

The thickness and mechanical properties of the reconstruction materials, including calvarian bone, had to be evaluated (for details see next sections), since to our knowledge there are no such data available in the literature.

When the deformation of a reconstruction material has been assessed by completing equation (1), the subsequent change in volume of the orbital cavity can be evaluated as follows: the sequence of events when an orbital floor fracture is reconstructed and deformation of the reconstruction material occurs is illustrated by Fig. 2. Fig. 2C and D depict the spatial relation between the deformation of a reconstruction material and the following change in volume of the orbital cavity. The increase in volume of the orbital cavity is equal to the part of the orbital content/eye that sinks through the orbital floor. This part can be considered to be the cap of a sphere with radius \( R \), of which the volume can be calculated using:

\[
V = \frac{1}{6} \pi h \left( 3r^2 + h^2 \right) \tag{2}
\]

where,

\[
V = \text{volume increase of the orbital cavity due to deformation of the reconstruction material (m}^3) \\
h = \text{deformation of the disk-shaped implant (m)} \\
r = \text{radius of the circular orbital floor defect (m)}
\]

Using equations (1) and (2), the increase in volume of the orbital cavity when deformation of the reconstruction material occurs can be calculated.

Now that we can quantify the deformation of the reconstruction material and subsequent volume increase of the orbit, it is the question to what extent volume increase may occur, before enophthalmos emerges. Evaluations in patients with blowout fractures of the orbital floor by Ploder et al. revealed that an increase of orbital volume of as little as 0.7 cm\(^3\) can be associated with enophthalmos (Ploder et al., 2002). This means that deformation of reconstruction materials leading to an increase of the orbital volume \( \geq 0.7 \text{ cm}^3 \) should be avoided at all costs. Since the best possible reconstruction of the orbital floor is qualified as the pre-existent anatomical situation of the orbital floor, another question arises, namely: how to quantify this anatomical situation for use as a reference.

The most ideal situation would be that there is no deformation at all of reconstruction materials. However, a certain degree of deformation will always occur. It is known that the orbital floor too can deform when subjected to a (sudden) increase in pressure load. Hence not every trauma leads to a fracture. Whether it bends or breaks depends on the magnitude of the increase and anatomical differences amongst humans. We used the ability of the human orbital floor to bend under a pressure load to quantify the anatomical situation by determining the mechanical properties of the human orbital floor and assessing the behavior of the (intact) orbital floor subjected to the aforementioned pressure load of 13 mmHg. It was chosen to use the assumed traumatic pressure (13 mmHg) instead of the physiologic pressure (6.5 mmHg), because as not every trauma to the orbit and orbital floor leads to an

![Fig. 2. Reconstruction of orbital floor fractures. A) Lateral view of the normal human orbit, the orbital contents rest on the orbital floor. In the figure soft tissue (a), bone tissue (b) and the maxillary sinus (c) can be discerned. B) As a result of trauma, the orbital floor has fractured and the contents of the orbital cavity sag into the maxillary sinus. This leads to an increase of the orbital volume and enophthalmos. C) Restoration of the anatomy of the orbital cavity by reconstruction of the orbital floor with an implant (d). D) Inadequate anatomical reconstruction of the orbital floor or deformation of the implant and sagging of the orbital content into the maxillary sinus can lead to an increase of the orbital volume and enophthalmos. The increase in volume of the orbital cavity, which is shown as part of a sphere, can be calculated according to equation (2).](image-url)
orbital floor fracture, it still can give rise to a temporary increase in pressure due to intra orbital hematoma and swelling.

The evaluation of the thickness and mechanical properties of the human orbital floor is described in the section ‘mechanical properties’ and ‘structural analysis of orbital floor bone’.

To evaluate the orbital floor correctly, a different mathematical model needs to be used (Fig. 3). As the orbital floor is part of the skeleton, the orbital floor is considered to be fixed to a support structure. The appropriate equation is (Young, 1989):

\[ h = \frac{pr^4}{64D} \]  

where,

- \( h \) = deformation of the human orbital floor
- \( p \) = applied load
- \( r \) = radius of the orbital floor: \( r = 0.0132 \) m, based on the evaluations that the entire orbital floor is 5.5 cm² (Ploder et al., 2002).
- \( v \) = Poisson’s ratio of the material from which the implant is prepared (assumed to be 0.3).
- \( D \) = flexural rigidity of the human orbital floor defined as:

\[ D = \frac{Et^3}{12(1 - v^2)} \]  

In this equation

- \( E \) = flexural modulus of the human orbital floor
- \( t \) = determined thickness of the human orbital floor

After the deformation of the orbital floor has been calculated the increase in volume of the orbital cavity is given according to equation (2) as mentioned before. The thus obtained value will serve as reference for anatomical reconstruction.

2.2. Orbital floor and calvarian bone harvest

Fifteen fresh-frozen cadaveric heads (12 male and 3 female, aged 70 ± 8.3 years (mean ± SD)) were obtained from the Department of Anatomy, University of Groningen, yielding 30 orbital floors. The orbital walls of each of these 15 specimens were exposed through a transcutaneous periorbital incision and subsequent removal of the orbital content. Using a water-cooled bur (model Aesculap Elan-E) samples for mechanical testing were taken from the medial part of the orbital floor, medial of the infraorbital nerve and lateral of the medial wall, as shown in Fig. 4.

Because calvarian bone was selected as reconstruction material for evaluation, samples of the outer table of the calvarian parietal bone were taken from 5 cadavers (\( n = 5 \) was considered adequate sample size for measuring). The calvarian bone was exposed through a transcutaneous incision. Four 10 mm cranial bur holes were drilled with a water-cooled craniotome (model Aesculap Elan-E) and connected by a fraise. The full thickness calvarian plate was then removed and samples of the outer table were taken by splitting off the outer table from the inner table with a chisel. Both orbital floor and calvarian bone samples for mechanical testing were preserved in a solution of 0.9 wt% NaCl solution.

2.3. Structural analysis of orbital floor bone

Structural analysis of the collected samples of orbital floor bone was performed using micro-computed tomography (micro-CT) scanning on a GE eXplore Locus SP scanner at 8 μm resolution. The scan was carried out at 80 kV voltage, 80 mA current and 3000 ms exposure time, without filter. Scans were stored and thickness of samples was determined using GE MicroView Analysis Software (freeware). Thickness was measured at three points per sample (Fig. 5).

2.4. Selected reconstruction materials used for evaluation

Besides calvarian bone, four commonly used reconstruction materials were selected (Fig. 6). Both non-resorbable and resorbable alloplastic implants were selected for evaluation: Micro Orbital Titanium Mesh (KLS-Martin, Germany), ResorbX (50/50 poly-D,L-lactide) (KLS-Martin, Germany), Medpor (polyethylene) (Porex Surgical, USA), Perthese (reinforced silicone sheet) (Perouze Plastie, France). The materials were evaluated for their deformation over a series of theoretical orbital floor defects in a mathematical engineering model.

2.5. Mechanical properties

The mechanical properties of the reconstruction materials including calvarian bone and the orbital floor samples were evaluated in a three-point bending test. Three-point free supported bending tests were performed on a DMA Perkin Elmer universal tensile test machine operated at a crosshead speed of 0.5 mm/min, according to ISO 178-1975 (E). Samples from orbital floors and calvarian outer table were tested to determine their flexural modulus (E-modulus). Samples from the alloplastic materials, used for orbital floor reconstruction, were tested in three-fold. The length and width of the test samples were 25 mm and 10 mm, respectively. The thickness of the test samples varied from 0.3 mm to 1.0 mm, depending on the type of reconstruction material (see Table 2). Samples from the orbital floor and calvarian bone were

Fig. 3. Technical illustration of the model in which the deformation of the orbital floor is evaluated. Note that here the orbital floor sample is not freely-supported, but fixed at the edges (this is indicated by the shaded areas in the axial and lateral views of the model).

Fig. 4. A) Photograph of the harvest site of the medial part of the orbital floor in human cadavers. B) Photograph of harvested samples of the human orbital floor. Note the thinness of the samples.
15 mm and 5 mm in length and width, respectively. The thickness of the orbital floor samples was determined by micro-CT (see Sections 2.3 and 3.1). The thickness of the calvarian bone samples was measured using a digital calliper, and ranged from 1.5 to 3.0 mm. The samples of the orbital floor bone were mounted in the test set-up with the side facing the maxillary sinus downwards and the orbital facing side upwards. Both the samples from the alloplastic implants as well as samples from the outer table of calvarian bone were mounted in the test set-up according to the position as used for reconstruction.

3. Results

3.1. Mechanical properties of reconstruction materials and human orbital floor

The results for the bending test of the calvarian bone samples was measured using a digital calliper, and ranged from 1.5 to 3.0 mm. The samples of the orbital floor bone were mounted in the test set-up with the side facing the maxillary sinus downwards and the orbital facing side upwards. Both the samples from the alloplastic implants as well as samples from the outer table of calvarian bone were mounted in the test set-up according to the position as used for reconstruction.

The harvest procedure resulted in 30 orbital floors of which 28 were included (samples of 1 female cadaver had to be excluded because of irregularity of the sample dimensions). The results for the bending tests and thickness evaluation by micro-CT are presented in Table 3. The determined values of the flexural modulus of the orbital floor exhibited a non-parametric distribution with median 2555 MPa and Inter Quartile Range (IQR) 1260–4550 MPa. In some instances major differences were found in mechanical properties between the right and left orbital floor in the same cadaver. Micro-CT analysis showed a parametrical distribution for the thickness of the orbital floor samples with mean thickness 0.26 ± 0.1 mm.

3.2. Calculating volume increase

Using the equations as described, a Microsoft Excel spreadsheet was constructed to facilitate the calculations for the different materials (the Microsoft Excel spreadsheet is freely available at: www.omf-research.com). Using this spreadsheet, the deformation and the corresponding increase in volume of the orbita were calculated for the orbital floor and different reconstruction materials including calvarian bone. As stated, the evaluated defect categories 1, 2, 3 and 4 (as described by Jaquiéry et al.) were considered to correspond to a defect size of 1, 2.5, 4 and 5.5 cm², respectively.

The volume increase of the orbital cavity regarding the use of the different reconstruction materials over the series of (theoretically) defined (orbital floor) defect sizes is graphically presented in Fig. 7. Analogous to the variation in the defect size of the theoretical orbital floor defects (Cat. 1–4) also the evaluated thickness for the different materials was varied (Fig. 6, panels A–D).

Note that the model in the evaluation of the human orbital floor in all cases used the mean measured thickness of the orbital floor (0.26 mm) and the evaluated ‘defect size’ was always category 4 corresponding to 5.5 cm². The volume increase was calculated
for the median modulus (2550 MPa) as well as for the IQR (Q1 1260 MPa, Q3 4550 MPa). This led to a constant volume increase of the orbital volume (0.03 cm³, Q1 0.1 cm³, Q3 0.02 cm³) for the data on the human orbital floor, with the IQR creating some sort of ‘physiologic band width’ for an ‘ideal’ reconstruction. As stated, no volume increase is regarded the most ideal reconstruction.

It can be seen that the orbital floor, considered in the ‘fixed’ situation, showed some increase in orbital volume under the applied pressure load. Regarding the reconstruction materials the Titanium Micro Orbital Mesh led to the least increase in orbital volume, closely followed by calvarian bone and ResorbX. The more flexible materials Medpor and Perthese showed bigger increases in orbital volume compared to the aforementioned materials. Depending on the evaluated thickness their performance improved. Overall, the volume of the orbital cavity increased, as expected, when the reconstruction materials were thinner. Also an enlarged defect size led to an increase in orbital cavity volume.

Table 4 shows the implementation of the data for the different implant materials regarding the reconstruction of orbital floor defects.

4. Discussion

Incorrect reconstruction of orbital wall defects can lead to volume increase of the orbital cavity with complications like enophthalmos, hypoglobus and diplopia. Hence most important is an anatomical reconstruction that ensures pre-existent orbital cavity volume. Therefore, sagging of implants must be avoided. The lack of clear guidelines for orbital floor reconstruction regarding the relation between the different implant materials and defect size can lead to peri- and postoperative sagging of implant material. A pre-operative evaluation of the behaviour of the different implant materials over the orbital floor defect could avoid (late) complications. Therefore, we developed a mathematical engineering model of the orbital floor in which all types of implant material, while taking their thickness into account, can be evaluated over a multitude of orbital floor defects. When applying this model it could be shown that most of the materials tested, with the exception of Perthese, are suitable for reconstruction of a fracture of the orbital floor (Table 4).

Although previous literature has recognized the relation between degree of enophthalmos, defect size and orbital cavity volume, this relation has, to our knowledge, not been linked in a mathematical way to the reconstruction materials used in orbital wall surgery (Ahn et al., 2008; Al-Sukhun et al., 2006; Cunningham et al., 2005; Ploder et al., 2002). Literature mainly focused on the treatment of orbital floor fractures, on the timing of surgical intervention and whether surgical intervention is necessary (Bowers, 1964; Burnstine, 2002; Kontio and Lindqvist, 2009). Although efforts have been made to formulate recommendations concerning the choice of implant material(s) with regard to defect size, it often remained limited to statements like ‘small to medium sized defects can be reconstructed with more flexible materials (silicone, polydioxanone), while large defects are best reconstructed with rigid materials like titanium or a combination of materials’, thus leaving the surgeon (again) without an advice that takes thickness and implant material in relation to defect size into account (Jaquier, 2010).

The novelty of our model is that it can assess the (minimal) thickness needed for the implant materials to limit the volume increase of the orbital cavity to the physiologic band width or below when the defect size is known. However, our model might not precisely quantify the orbital volume increase. Firstly, the orbital floor is not flat. In fact, the anatomy of the orbital floor is very complicated as the shape of the orbital floor ranges from sinusoidal to more or less flat configurations, and differs within and between individuals (Metzger et al., 2007; Nagasao et al., 2006). However, as shown by Nagasao et al. the orbital floor in children and the young and middle aged is rather flat in an anterior–posterior direction, while in the elderly there is more of a curvature (Nagasao et al., 2007). Moreover, the paper by Nagasao et al. showed that the majority of orbital floor fractures occurred in young and middle age patients (Nagasao et al., 2007). This supports our choice for using an easy to apply flat model. Secondly, the assumed pressure load on the orbital floor is based on the retrobulbar pressure which in normal conditions ranges from 3 to 4.5 mm Hg. Based on the assumptions by Cordewener et al. the pressure load on the orbital floor was set at 13 mm Hg. We believe that this value approaches the physiologic pressure load (due to hematoma and edema of structures of the orbital content) after a trauma. Nevertheless, the

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Table 2
Mechanical properties of commercially available implants used in the surgical reconstruction of orbital floor fractures and the materials from which they are prepared. Also the mechanical properties of calvarian bone are presented.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Flexural modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Orbital Mesh</td>
<td>6533 ± 453</td>
</tr>
<tr>
<td>ResorbX</td>
<td>1283 ± 140</td>
</tr>
<tr>
<td>MedPor</td>
<td>119 ± 6</td>
</tr>
<tr>
<td>Nuance</td>
<td>3.9 ± 0.1</td>
</tr>
<tr>
<td>Calvarian bone</td>
<td>2790 ± 1338</td>
</tr>
</tbody>
</table>

Table 3
Data on thickness, as measured by micro-CT, and flexural modulus of right and left orbital floor samples. The excluded samples are not shown.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Sex</th>
<th>Age (yr)</th>
<th>Orbital floor</th>
<th>Thickness* (mm)</th>
<th>Flexural modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>55</td>
<td>Right</td>
<td>0.19</td>
<td>4600</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>70</td>
<td>Left</td>
<td>0.14</td>
<td>4600</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>73</td>
<td>Right</td>
<td>0.21</td>
<td>2680</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>60</td>
<td>Left</td>
<td>0.27</td>
<td>1950</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>72</td>
<td>Left</td>
<td>0.15</td>
<td>2900</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>66</td>
<td>Left</td>
<td>0.25</td>
<td>9170</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>86</td>
<td>Right</td>
<td>0.19</td>
<td>810</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>69</td>
<td>Right</td>
<td>0.26</td>
<td>1890</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>79</td>
<td>Left</td>
<td>0.36</td>
<td>730</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>64</td>
<td>Left</td>
<td>0.19</td>
<td>370</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>60</td>
<td>Right</td>
<td>0.28</td>
<td>2540</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>78</td>
<td>Left</td>
<td>0.21</td>
<td>2340</td>
</tr>
<tr>
<td>13</td>
<td>F</td>
<td>64</td>
<td>Left</td>
<td>0.39</td>
<td>3600</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>79</td>
<td>Left</td>
<td>0.36</td>
<td>1050</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>70 ± 8.3</td>
<td>Left</td>
<td>0.35 ± 0.1</td>
<td>Median 2555 with IQR 1260–4550</td>
</tr>
</tbody>
</table>

* Mean thickness after evaluation by micro-CT.
lack of more accurate data concerning the intraorbital pressure(s) and force(s) necessitated us to build the model around this estimated pressure load. Next to a physiologic pressure load, there also might be incidentally high pressure loads like, e.g., high blood pressure due to postoperative pain and Valsalva maneuvers being involved. Regarding high blood pressure, incidental increases in blood pressure are corrected for by the elasticity of the blood vessels and autoregulation system of the human body itself. Regarding the rise in pressure caused by the Valsalva maneuver, not only the pressure in the orbit is increased, but also in the tissues surrounding the orbit. These pressures act as counter-act pressures. Hence, it can be concluded that the pressure gradient over the orbital floor/walls is negligible unless the orifice of the maxillary sinus is blocked. A third deficit of the model is that the in vivo behaviour of the different materials cannot be predicted, again the lack of accurate data on this topic is to blame. It is, however, not inconceivable that precisely the more plastic and bioactive materials act differently in the in vivo situation. Resorbable implants, like ResorbX e.g., lose their mechanical properties, thus strength and rigidity, during degradation. For polylactic acid derived implants reductions up to 60% of the initial values after 12 weeks of implantation are known (Heidemann et al., 2001). This could lead to sagging and subsequent (late) enophthalmos, especially when large (cat 3–4) defects are involved. In the case of resorbable polymers it is important that the tissue formed at the site of the defect should be strong enough to withstand the pressure load of the orbital content. The model does not consider or correct for this behaviour of biodegradable implant materials, including (autologous) bone, it only evaluates materials in their initial state. This has to be recognized when reconstructions with these materials are carried out.

**Fig. 7.** Relation between reconstruction material, defect size and volume increase. The dotted line 'Ref' represents the reference line corresponding to a volume increase of 0.7 cm³. Line Q₁ and Q₃ are the borders of the IQR. The IQR provides a physiological band width which represents the volume increase of the orbital volume due to deformation of the orbital floor under pressure. Note that a volume increase below the level of the IQR is even better. Thickness of the reconstruction materials is varied from 0.3 mm to 1.0 mm, panels A–D, respectively.

A. 0.3 mm thickness

B. 0.6 mm thickness

C. 0.8 mm thickness

D. 1.0 mm thickness

- Micro Orbital Mesh
- Medpor
- Calvarian Bone
- Perthes
- ResorbX
because there is a risk for sagging once the biodegradable material has lost its mechanical properties. Nevertheless, we have the opinion that the thickness of the implant material does not seriously affect the measured outcomes for the different materials.

Another model described in literature to test the strength of reconstructive materials for reconstruction of orbital floor defects is the model by Hwang et al. (Hwang and Kim, 2010). In that model of the orbital floor pre-bent reconstruction materials were evaluated for their supporting strength. With their model, the authors could show that certain materials are indeed suitable to prevent development of enophthalmos. The reconstruction materials to be tested were fixed to the anterior part of the orbit or orbital rim. However, in contrast to our model, in the model of Hwang et al. the reconstruction materials were not supported along the lateral, medial and posterior borders. This is a limitation of that model (Hwang and Kim, 2010). By contrast, our model presumes that the reconstruction materials are supported along their complete periphery by remaining stable parts of the damaged orbital floor. Although there are great dissimilarities between both models, both studies showed that an increase in orbital volume indeed results in enophthalmos and that the suitability of a material to restore a defect can indeed be tested a priori. However, while in our model the increase in volume of the orbit and the effect of a specific material to reduce enophthalmos can be calculated at chair side, for the model developed by Hwang et al. the efficacy of every material that is considered to restore the defect has to be separately examined in a laboratory setting.

From the results for the different reconstruction materials assessed by the model it can be concluded that not all materials are suitable when varying defect sizes are considered (Table 4). Surgeons should be aware of the fact that localization of the defect also plays a role in the development of enophthalmos. Defects of the posterior part of the medial orbital wall, for example, can lead to severe enophthalmos as the posterior part of the orbital wall together with the lateral orbital wall are the main support for a correct anterior projection of the globe (Hammer, 2002). By contrast, defects anterior to the equator of the globe do not influence the position of the globe and thus are not associated with development of enophthalmos.

It seems safe to treat category 1–4 fractures with titanium, bone, poly(lactide) and polyethylene, but the configuration of the fracture and the demands for the configuration of the implant material in order to achieve an anatomical reconstruction could have an effect on implant choice. Unlike titanium meshes for example that can be used in stable configurations, this is not the case for polyethylene. Furthermore, care should be taken when (thin) flexible materials are applied as is illustrated when silicone is used for reconstruction of category 3–4 defects. The volume increase measured due to deformation of the orbital floor samples could be considered as an ideal situation, although it should be mentioned that all materials, especially when coming in minimal thickness, will show a certain degree of volume increase due to sagging. This cannot be avoided but should be kept to a minimum.

It is not the intention of the model to predict or recommend whether to treat or not to treat orbital floor fractures, nor to recommend degradable over non-degradable materials or vice versa. Moreover, the model can give an overview of the suitability of implant materials in relation to defect size and help to choose the appropriate (minimal) thickness of reconstruction materials in a way to minimize orbital volume increase. Therefore the proposed model could be useful in the pre-operative management of orbital floor fractures by helping the surgeon to choose a suitable reconstruction material with the correct thickness. The model is, however, less suitable for secondary reconstructions. Since atrophy of the very complex musculoseptal apparatus and orbital adipose tissue are unpredictable, a correction for the relative increase in volume of the orbit is impossible. Only, in case the extent of volume increase of the orbital content is known, it is theoretically possible to incorporate such data in our model. In addition, shaping of the reconstruction material to correct the position of the globe is “surgeon-work” and the outcomes are dependent on the skills of the surgeon.

Although the medial wall is often involved in orbital floor fractures we were not able to implement the medial wall in our model. Unlike the orbital floor, being a simple osseous layer that separates the orbit from the maxillary sinus, the medial wall is determined by different irregular honeycomb-like cells of the ethmoidal complex. Consequently pressure loads applied to the medial wall are not uniformly distributed and therefore make it much more difficult to implement in our model. However, strengthened by the idea that if implant materials perform sufficiently in (isolated) orbital floor fractures, they will also in combined orbital floor and medial wall fractures, with respect to their mechanical properties. This makes the model theoretically suitable for the evaluation of orbital floor fractures combined with fractures of the medial wall.

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**References**


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