

Prediction of tissue decompression in orbital surgery

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Abstract

Objective. A method to predict the relationships between decompressed volume of orbital soft tissues, backward displacement of globe after osteotomy, and force exerted by the surgeon, was proposed to improve surgery planning in exophthalmia reduction.

Design. A geometric model and a poroelastic finite element model were developed, based on computed tomography scan data.

Background. The exophthalmia is characterized by a protrusion of the eyeball. Surgery consists in an osteotomy of the orbit walls to decompress the orbital content. A few clinical observations ruling on an almost linear relationship between globe backward displacement and tissue-decompressed volume are described in the literature.

Methods. Fast prediction of decompressed volume is derived from the geometric model: a sphere in interaction with a cone. Besides, a poroelastic finite element model involving morphology, material properties of orbital components and surgical gesture was implemented.

Results. The geometric model provided a better decompression volume estimation than the finite element model. Besides, the finite element model permitted to quantify the backward displacement, the surgical gesture and the stiffness of the orbital content.

Conclusions. The preliminary results obtained for one patient, in accordance with the clinical literature, were relatively satisfying. An efficient aid for location and size of osteotomies was derived and seemed to be able to help in the surgery planning.

Relevance

To our knowledge, this paper concerns the first biomechanical study of exophthalmia reduction. The approach permitted to improve the treatment of orbitopathy and can be used in a clinical setting.

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1. Introduction

Acquired exophthalmia is frequently observed in cases of thyroid diseases and especially in cases of Grave's disease which is associated with hyperthyroidy (Saraux et al., 1987). In these cases, it can be observed an excessive protrusion of the ocular globe outside the orbit, due to an increase of volume of the orbital content (fat tissues and ocular muscles), Fig. 1a. Besides its aesthetical and psychological consequences, the exophthalmia is often followed by an abnormal exposition of

the cornea and by the extension and/or the compression of the optic nerve and orbital blood vessels. Those factors can lead to a decrease of visual acuity and sometimes to total blindness. At worst, exophthalmia needs active therapy and often surgery to avoid serious complications. First the endocrinal dysfunction has to be stabilised with medicines or radiotherapy in the worst cases. Then surgical reduction of the exophthalmia is usually needed to decompress the orbital content.

Two surgical techniques can be used for this decompression. The first one aims at extracting a partial volume of fat tissues via an external eyelid incision (Olivari, 2001). The advantages of this method are its simplicity and the relative security during surgery since the optic nerve is far from the extracted fat tissues. The

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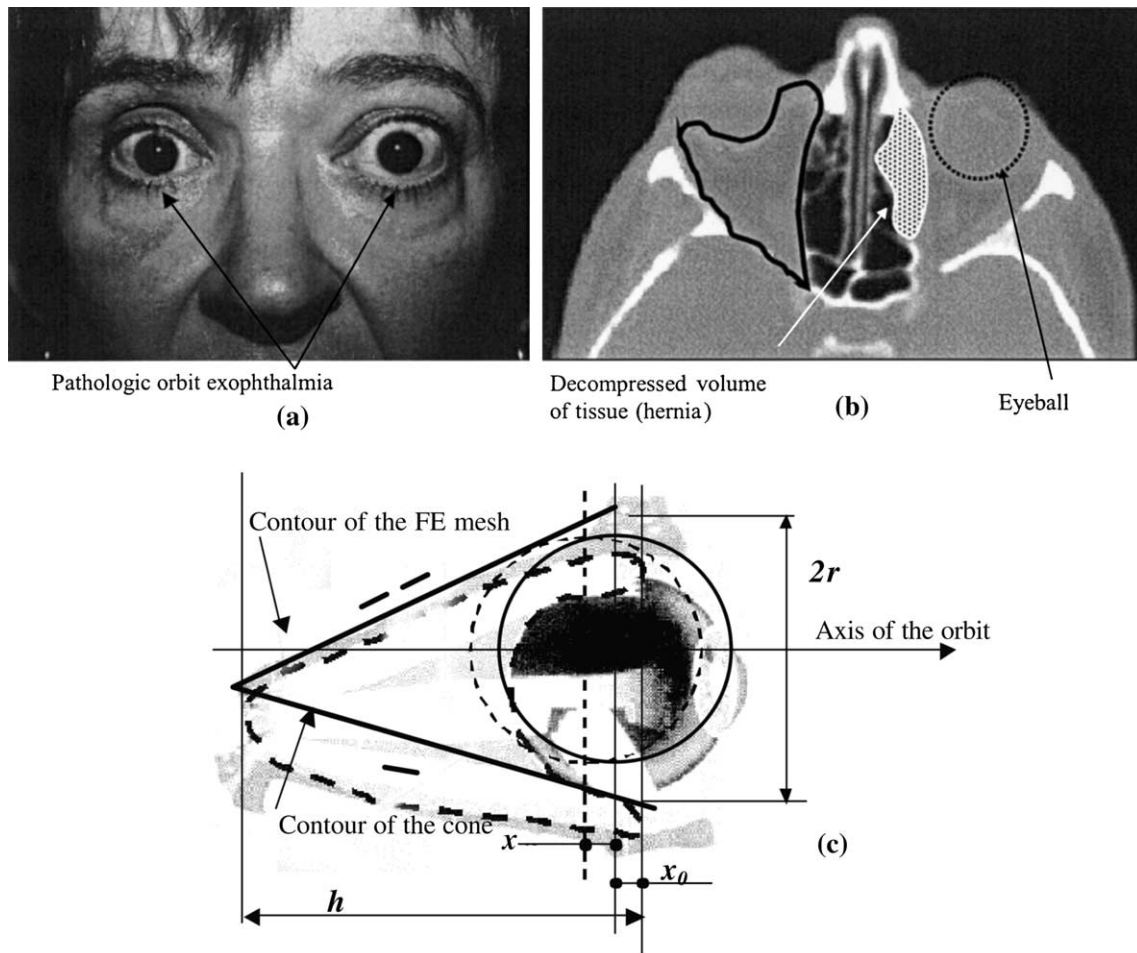


Fig. 1. Patients suffering from exophthalmia: (a) bilateral exophthalmia, (b) bilateral exophthalmia whose only the left eye has been treated: segmentation of the orbit; (c) Geometric model.

drawbacks are first a small backward displacement of the globe due to the limited volume of fat tissues in the eyelid region, the difficulty to know the exact amount of fat to be removed and an aesthetical risk for the patient since upper lid depression can be later observed. The second surgical technique aims at increasing the volume of the orbital cavity thanks to an osteotomy of one or several of the orbital walls (Wilson and Manke, 1991; Stanley et al., 1989). These osteotomies are completed by some cuts in the membrane containing the orbital soft tissues, in order to permit a fat tissue issue. An external pressure is additionally exerted by the surgeon onto the eyeball, during a few seconds. Consequently, some retro-ocular tissues can be evacuated through the hole, towards the sinuses. The advantages of this method are the conservation of the integrity of intra-orbital fat, a backward displacement of the eyeball that can be larger than with the other technique and the theoretical possibility, for the surgeon, to have a better prediction of the post-operative result. The drawback is the risk to cause perturbations in visual function (e.g. transient diplopia). The surgical procedure has therefore

to be very precise to avoid critical structures such as the optic nerve. Moreover this intervention is technically difficult since the eyelid incision is narrow and the operating field restrained; the surgery must be mini-invasive and specific tools to improve surgical planning would be really useful.

Up to now, very few results focusing on exophthalmia reduction appear in the literature. From a clinical point of view, the prediction of the surgically decompressed volume lies on observations and statistical analyses (Adenis and Robert, 1994): for a 1 cm^3 soft tissues decompression, a backward displacement from 1 to 1.5 mm is expected. From a biomechanical point of view, there are some works concerning the modelling of the ocular globe (Sagar et al., 1994; Uchio et al., 1999) and the intra-orbital soft tissues (Miller and Demer, 1999; Buchberger and Mayr, 2000), but none of them deals with exophthalmia reduction.

To improve surgery planning in exophthalmia reduction a method to predict the relationship between the decompressed volume of orbital soft tissues and backward displacement of the orbital globe after osteotomy

has been developed. In this paper, two complementary predictive models are proposed. First, a geometrical 2D model provides a rough evaluation of the decompressed tissue volume and second, a 3D poroelastic finite element model permits to simulate the surgical gesture. The clinical application concerns a patient suffering from a bilateral exophthalmia, whose only the left eye has been treated (Fig. 1b).

2. Methods

2.1. Three-dimensional reconstruction of the orbit

Horizontal computed tomography (CT) slices were collected for the whole patient skull (helical scan with slices reconstructed each millimeter). CT images were first segmented to extract the bone limits, the muscles and the optic nerve contours. The segmentation procedure was achieved manually through B-Splines definitions on each slice, as shown in Fig. 1b. The area of each segmented anatomical structure were deducted and then extrapolated over the whole slices to get the global volume. In-house software available for the surgeon has been developed in Visual C++ coupled with VTK graphical library (<http://public.kitware.com/VTK/>) and permitted a first 3D description of the orbital content.

2.2. Geometrical model

The eyeball was modelled by a sphere (radius r_0) lying on a homogeneous cone (the orbital cavity; depth h , radius of opening r), see Fig. 1c. During the decompression, the soft tissues were supposed to be constrained by the eyelid so that their extremity in this region is constant relative to the eyeball position (x_0). This assumption permitted to derive Eq. (1) expressing the relationship between the tissue-decompressed volume V and the backward displacement x of the eyeball.

$$V = \frac{\pi}{3}(r/h)^2(x^3 - 3x^2h + 3h^2x) \quad (1)$$

The sensitivity of parameters r and h were quantified using a perturbation technique. The first order Taylor expansion of V_{geo} led to the relative variation $\Delta V/V$ of the decompressed volume expressed by Eq. (2).

$$\frac{\Delta V}{V} = S_r \frac{\delta r}{r} + S_h \frac{\delta h}{h} + S_{rh} \frac{\delta r}{r} \frac{\delta h}{h} + O(r^2, h^2) \quad (2)$$

with

$$S_r = 2, \quad S_h = \frac{(3h - 2x)x}{3h^2 + (x - 3h)x} \quad \text{and} \quad S_{rh} = 2S_h$$

The depth h varied from 30 to 50 mm and the backward displacement x was between 0 and 10 mm. Usually, the average backward displacement obtained in a clinical

setting is around 5 mm. It was demonstrated by Eq. (2), that the sensitivity to r was constant ($S_r = 2$) and predominant by comparison with S_h (bounded to 0.37 for $h = 30$ mm and $x = 10$) and S_{rh} .

2.3. Poroelastic finite element model of the orbit

The eye ball was considered as rigid in comparison with the orbital soft tissue (fat, muscles and optical nerve). From a biomechanical point of view, its strain energy was therefore neglected in the model. In this preliminary study, the orbital content was considered as an homogenized material modelling the fat tissues, the muscles and the optic nerve. The fat tissues are predominant (approximately 3/4 of the volume) in this material and are mainly present in the flow through the osteotomy during the surgical intervention. Clinical observations (Saraux et al., 1987) describe the intra-orbital pathological fat tissues as the combination of an elastic phase composed of fat fibres (mainly collagen) and a fluid phase composed of fatty nodules saturated by physiological fluid.

The biomechanical modelling of the intra-orbital tissue was therefore achieved using a homogeneous poroelastic formulation of the finite element (FE) method, with fluid transport in saturated elastic porous media (FE software MARC[®], MSC Software Inc., Santa Ana, CA, USA). Two parameters of the poroelastic model, namely the porosity and the permeability, allow to take into account the retention of fluid, generally observed in clinical settings. The variational formulation of the coupled problem led to the finite element discretisation using nodal displacement and pore pressure as nodal variables (Biot, 1941).

The FE orbital cavity was meshed using three-dimensional 20-node hexahedrons (quadratic elements) involving three translation degrees of freedom for each node and a pore pressure for each corner node. The global meshing involved 6948 nodes, 1375 elements and 22 716 degrees of freedom. The Young modulus of the homogenized tissue was set to 20 kPa according to the soft tissue properties from the literature (Fung, 1993; Power et al., 2001). The Poisson ratio, set to 0.1, was inherent to the poroelastic modelling of soft tissue (Mow et al., 1980; Argoubi and Shizari-Adl, 1996).

The relaxation time of the fluid saturated porous media is highly related to the permeability. In intervertebral disk, complete relaxation occurred at night in almost 8 h and, in exophthalmia reduction, the relaxation time is around 10 s. A proportional rule using the relative permeability of disk as a reference ($k/\mu = 0.1$ mm⁴/N s, Simon et al., 1985) permitted to roughly estimate the permeability of the orbital content around 300 mm⁴/N s. The porosity of the homogenized orbital content was set to 0.4, also referring to the disk (Simon et al., 1985).

The mesh and the boundary conditions are shown in Fig. 2. Specific boundary conditions were defined to reproduce the surgical technique. Before the bony walls osteotomy, the tissues were confined in the orbit: the boundary conditions were nil displacement and total sealing effects at interface nodes. To model the bony wall osteotomy, nodes were fixed in terms of displacement to simulate the rigidity of the membrane surrounding the tissues, and they were released in term of sealing boundary conditions, to simulate cuts in this membrane due to the surgical gesture. The wall opening was located along the axis of the orbit in terms of percentage of the depth h . The osteotomy corresponding to the clinical data (derived from the post-operative CT scan) was located on the front of the orbit, at $h_{\%} = 62$, and had an area of 2.9 cm^2 .

To study the sensitivity of the model according to the size and the location of the wall opening, three other osteotomies were designed. Two locations were consid-

ered $h_{\%} = 50$ (back of the orbit) and 62 (front of the orbit) as shown in Fig. 2. In accordance with clinical feasibility, two sizes were considered in the ethmoid sinuses: medium osteotomy— 1.4 cm^2 and large osteotomy— 2.9 cm^2 , see Fig. 2.

Riemann et al. (1999) have shown that the intra-orbital tissues are characterized by an overpressure of 10 kPa due to the pathology. Therefore, an initial pore pressure was set to 10 kPa in the FE model to take into account the initial non-nil strain energy in the biological structures. This initial pressure was relative to the pressure applied to the orbit and meant that there was an overpressure of 10 kPa in the tissues. A relaxation time of 2 s was then needed to get pressure equilibrium. During this time, nodes located at the soft tissue/globe interface were free to move.

Since the eyeball is considered as a solid body, the force imposed by the surgeon was modelled as an imposed axial load (according to the long axis of the orbit) applied on an external node connected by rigid elements to the nodes of the tissue/globe interface (Fig. 2). This permitted to simply control the load on interface nodes via the resulting load applied on the external node. This imposed load was linearly applied in 2 s in the range $0\text{--}12 \text{ N}$ as shown in Fig. 3. No sliding and friction effects were considered in tangential directions and consequently, no contact analysis was needed. The backward displacement of the globe was derived from the FE computation tracking the displacement of the external node where the imposed load was applied.

The imposed load was maintained during 3 s , and then released. During the release phase, the osteotomy wall was maintained impermeable to avoid fluid flow back into the orbit. This phenomenon is clinically relevant as the fat tissues stay in the sinus after having been decompressed.

The tissue-decompressed volume was derived from the difference of fluid saturated mesh volumes before and after loadings. It was corresponding to the volume of outward fluid flow. The volume of solid phase was

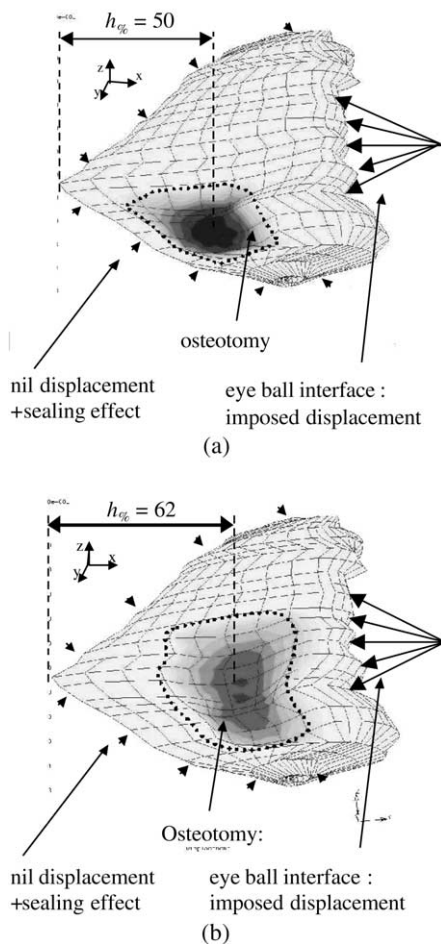


Fig. 2. Poroelastic FE model of the orbit: (a) medium osteotomy at the back of the orbit ($h_{\%} = 50$); (b) large osteotomy at the front of the orbit ($h_{\%} = 62$); greyscale: displacement field of the decompressed tissue out from the osteotomy (free solid displacement and free fluid movement).

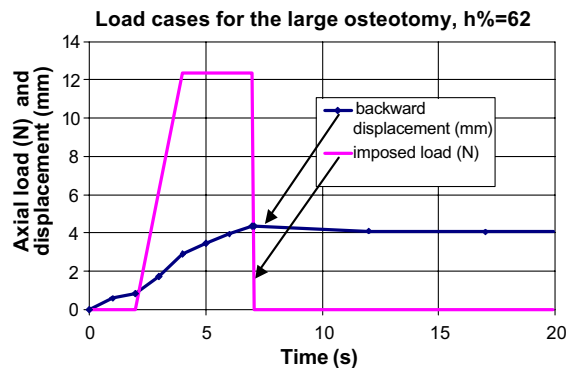


Fig. 3. Load applied to the globe and resulting backward displacement. After 20 s , the equilibrium is reached.

not taken into account in the decompressed volume computation since nil displacement were imposed as boundary conditions on nodes of the osteotomy wall.

3. Results

The clinical results of the exophthalmia reduction, measured from the patient CT scans as described in paragraph 2.1, were respectively 3.6 cm³ for the decompressed volume and 2.9 cm² for the sinuses wall osteotomy ($\pm 14\%$ due to errors measured on 15 segmentation cycles repeated by a single user). The central zone of the osteotomy was located at $h_{\%} = 62$. The backward displacement of the eyeball was about 4 mm. The magnitude of load of 12 N applied by the surgeon on the eye ball (and used as imposed load in the FE model) was measured using a custom designed sensor developed in the laboratory.

The 3D reconstruction of the orbital components permitted to quantify the radius of the orbit opening, $r = 18$ mm and the depth, $h = 42$ mm. These values, introduced in Eq. (1), gave the tissue-decompressed volume V_{geo} , expressed by Eq. (3). The tissue-decompressed volume V_{fem} derived from successive FE computations was linear and was described by Eq. (4) for the large size osteotomy (2.9 cm²) located at 26 mm ($h_{\%} = 62$) and corresponding to the wall opening reconstructed from the post-operative CT scan.

$$V_{geo} = a_1x - a_2x^2 + a_3x^3 \tag{3}$$

$$V_{fem} = b_1x \tag{4}$$

where V is in cm³ and x is in cm, $a_1 = 1.018$ cm², $a_2 = 2.4 \times 10^{-2}$ cm, $a_3 = 2 \times 10^{-4}$ unless dimension and $b_1 = 0.575$ cm².

Both volumes V_{geo} and V_{fem} were close to a linear function of the displacement x since the significant coefficients were respectively 1.018 for the geometrical model and 0.575 for the poroelastic FE model (the coefficient for x^2 and x^3 are far lower). This result is highlighted in Fig. 4. The geometric model provided satisfying predictive results. Indeed, it gave a volume of 3.69 cm³, which is very close to the clinical result (3% greater). The FE model with a frontal (at $h_{\%} = 62$) large size osteotomy (derived from the clinical data) gave an estimation of the decompressed volume of 2.3 cm³, 36% lower than the clinical result.

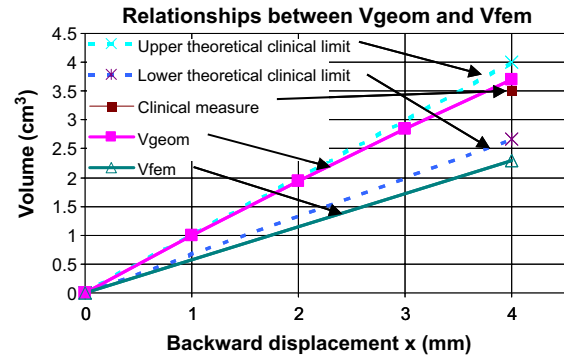


Fig. 4. Relationships between decompressed tissue volume and backward displacement of the eyeball, derived from the geometric and the FE models.

Table 1 summarizes those results, and gives a comparison of the backward displacement of the two models. Since the backward displacement is an input of the geometrical model, there is no backward displacement difference between this model and the clinical measurements. Concerning the FE model, the backward displacement discrepancy with the clinical result was very small (2%). Differences between the two models were much more important in terms of decompressed volume: while the geometrical model was quite close to clinical data (a 3% discrepancy), the FE model under-estimated the volume (36% lower than clinical measurements).

Table 1 also plots the stiffness values for the clinical case and for the FE case. In vivo pre-operative measurements of the surgical gesture are under development. The preliminary measurements show that for an average load of 12 N, a displacement of 5 mm is obtained, which corresponds to an orbital content stiffness of 2.4 Nmm⁻¹. This value was measured while the load is maintained constant, so that the displacement is maximal. The predicted stiffness derived from the FE model was, at this point, 2.85 Nmm⁻¹ (load: 12 N, displacement: 4.34 mm). Stiffness discrepancy was therefore around 19% in that case.

Table 2 presents the results for the four osteotomies (two sizes and two locations) simulated with the FE model for an imposed load of 12 N. The backward displacements, the decompressed volumes and the stiffness presented in this table point out the influence of the size and the location of the osteotomy. Indeed, the backward displacement measured for the four cases

Table 1

Comparison of the geometrical and FE results with the clinical measurements, for the backward displacement, the volume of decompressed tissue and the stiffness

| | Clinical results | Geometrical model | Finite element model (large frontal osteotomy) |
|--|------------------|-------------------|--|
| Backward displacement (mm) | 4 | 4 (+0%) | 4.07 (+2%) |
| Decompressed volume (cm ³) | 3.5 | 3.69 (+3%) | 2.30 (-36%) |
| Stiffness (N/mm) | 2.4 | None | 2.85 (+19%) (at $t = 7$ s) |

Table 2

Backward displacement, volume of decompressed tissue and maximum stiffness given by the FE model for a load of 12 N

| | Finite element model | | | |
|--|--------------------------------------|---------------|---------------------------------------|---------------|
| | Large osteotomy: 2.9 cm ² | | Medium osteotomy: 1.4 cm ² | |
| | $h_{\%} = 62$ | $h_{\%} = 50$ | $h_{\%} = 62$ | $h_{\%} = 50$ |
| Backward displacement (mm) | 4.07 | 3.39 (-17%) | 2.94 (-28%) | 2.71 (-33%) |
| Decompressed volume (cm ³) | 2.30 | 2.22 (-3%) | 1.66 (-28%) | 1.76 (-23%) |
| Maximum stiffness (N/mm) | 4.27 | 3.24 (-24%) | 6.30 (+48%) | 4.69 (+10%) |

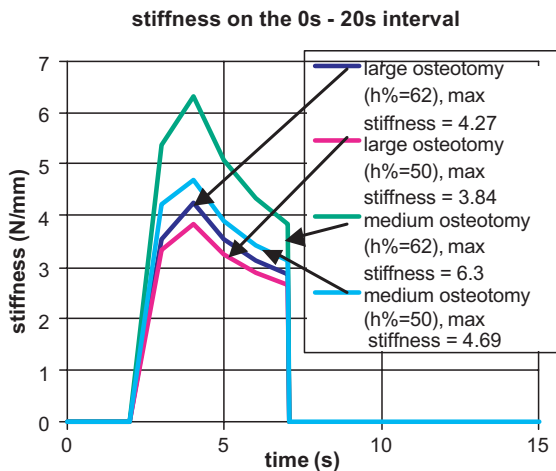


Fig. 5. Stiffness of the orbital content (ratio axial load–backward displacement) for two sizes and two locations of osteotomies ($h_{\%} = 62\%$ for the front and 50% for the back of the orbit). After 10 s, the stiffness decreases to 0 linearly.

showed significant differences: from -17% to -33% compared to the large frontal osteotomy simulated with the finite element model. Concerning the decompressed volume, the variations of the results for the four osteotomies range between -3% and -28% . The force–displacement relationships, i.e. the stiffness, for the four cases, is time dependant and is plotted in Fig. 5. Its maximum value (at $t = 4$ s) was used in Table 2, and range between -24% and $+48\%$ compared to the large frontal osteotomy.

4. Discussion

The geometrical model is a powerful tool for a first estimation of the volume of decompressed tissue in the pre-operative diagnosis, and it seems in good agreement with empirical clinical observations (Adenis and Robert, 1994; Jin et al., 2000, ratio ≈ 1 between eye ball backward displacement and tissue-decompressed volume). As demonstrated by the sensitivity analysis developed in paragraph 2, the radius of the orbit opening seemed to be a parameter requiring attention during the CT scans segmentation.

But the geometric approach did not permit to predict the impact of the surgical technique: size and location of

the wall osteotomy, and clinical feasibility of the force exerted by the surgeon. These two points were addressed by the poroelastic FE model.

The FE simulation of the surgery (with the large size osteotomy at $h_{\%} = 62$) provided a quite precise estimation of the globe backward displacement but with a significant error in the simulated decompressed volume. From our point of view, those results must be considered with caution. Indeed, the FE parameters (E , ν and k) were chosen in order to fit data and to be still in accordance with rheological data published in the literature. This means that those parameters must be more extensively validated. In particular, other patients' exams must be collected and corresponding simulations quantitatively evaluated.

In term of decompressed volume, results showed that the large size osteotomy seems to be more efficient from a clinical point of view since, for the same imposed load, it provided a greater decompressed volume and a higher backward displacement (Table 2). Concerning its position, the difference of approximately 5% between the frontal and back osteotomies is not enough important, compared to the size of the mesh elements, to conclude in a predominance in the position. Nevertheless, the results in term of backward displacement seem to be favourable to a frontal osteotomy since both frontal osteotomies provide greater backward displacement than for osteotomies at the back. These observations seem to point out that a large frontal osteotomy may be optimal.

Table 1 shows that the decompressed volume seems to be not linearly dependant on the size and the location of the osteotomy. Indeed, for an osteotomy twice as small (between the large one of 2.9 cm² and the medium one of 1.4 cm²), a decompressed volume of 28% smaller is produced. Finally, the FE model evaluates the slight forward displacement of the globe that appears after releasing the load.

5. Conclusion

The preliminary results obtained for one patient, in accordance with the clinical literature, were satisfying and may help in the improvement of the surgical planning of the exophthalmia reduction: the geometrical

model to estimate the decompressed volume (with a estimation error of 3%) and the FE model to simulate the osteotomy and to compute the resulting backward displacement (with a prediction error of 2%) and the orbital tissue stiffness (with a estimation error of 19%). However, it must be kept in mind that (1) the study is based on only one clinical case and (2) that the reliability of quantitative value obtained can be altered by uncertainties of orbital tissue material properties.

As a perspective, thanks to the powerful FE approach, it will be possible to differentiate the anatomical components (optic nerve, muscles and fat tissue) to rank their role in the global biomechanical behavior of the orbit. The integration of the muscles in the FE model is the next step of our study. In the future, the robustness of the approaches (geometric model and FE model) will be reinforced thanks to a clinical study involving a large base of patients whose data are available at the hospital.

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