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Finite element analysis of the human orbit. behavior of titanium mesh for orbital floor reconstruction in case of trauma recurrence

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Abstract

Introduction: The Authors' main purpose was to simulate the behavior of a titanium mesh implant (TMI) used to reconstruct the orbital floor under the stress of a blunt trauma.

Materials and methods: The orbital floor of a previously validated finite element model (FEM) of the human orbit was numerically fractured and reconstructed by a simplified TMI. Data from a CT scan of the head were computed with MICMICS (Materialise, Louvain, Belgium) software to re-create the skull's geometry. The meshing production, the model's properties management and the simulations of blunt traumas of the orbit were conducted on HYPERWORKS® software (Altair Engineering, Detroit, MI, USA). Some of the elements of the orbital floor were selected and removed to model the fracture; these elements were duplicated, their characteristics being changed by those of titanium to create a TMI covering this fracture. A 3D FEM composed of 640 000 elements was used to perform 21 blunt trauma simulations on the reconstructed orbit.

Results: In 90,4% (19/21) of the tests conducted, the TMI, whether free from any bony attachment or screwed to the orbital rim, has tended to move in the orbit and / or to deform.

Discussion: In the event of traumatic recurrence, which is not rare, TMIs may deform in a "blow-in" motion and threaten intra-orbital structures.

Keywords: finite element analysis; maxillofacial; trauma recidivism; orbit; biomechanics

Introduction

Titanium mesh implants (TMI) is commonly used for orbital floor fracture reconstruction. These devices have proven their effectiveness: they provide a reliable support for the orbital contents, optional screwing of the TMI to the orbital rim prevents secondary displacement. Their relative stiffness may however become a potential disadvantage in case of recurrent injuries as the implant may become distorted and behave as a penetrating foreign body able to threaten the intra-orbital content (eyeball, nerves, vessels) [1]. Studying the behavior of these implants in case of trauma recurrence may help to minimize their potential dangerousness. Our purpose was to simulate the behavior of a TMI used to reconstruct a fractured orbital floor of a previously validated FEM under the stress of blunt traumas.

Materials and methods

A 3D FEM of a human orbit which had previously been developed and validated by our team [2] was used in this study. Numerous simulations of blunt traumas of the orbit were run on Hypercrash® version 12.0 ((Altair Engineering, Inc., Detroit, MI, USA) by using a FEM of a metallic cylinder impactor (m=300-400g). The impactors was computed in order to hit the inferior rim of the orbit (acceleration =6-7m.s^{-1}). For each test, both the weight and acceleration of the impactors were modulated; we sought to reproduce a blunt trauma equivalent to a straight punch [3]. The impacts successively affected an empty orbit, and then an orbit filled with fat and an eyeball. In both cases, the orbital floor was fractured and rebuilt by a simplified TMI (figure 1)

The first step was to model a fracture of the floor of the orbit on our model. Some of the elements of the orbital floor were selected and removed, according to a fracture pattern consistent with those usually encountered in clinical practice: The fracture is anterior, and measures approximately 2.5cm²

The second step was to model a TMI to reconstruct the fracture thus obtained. We duplicated the elements removed in the previous step, and changed their biomechanical characteristics by those of titanium. (Density = 4500 kg / m^3, Young's modulus E = 114.10^3 MPa, Poisson's ratio ν = 0.34). We also duplicated a zone of elements around the fracture, so that the TMI could rest on the floor of the orbit and not fall into the maxillary sinus at the beginning of the simulations. The geometry of the mesh thus obtained is detailed in figure 2.

The impacts were located on the inferior orbital rim. 21 tests were simulated and included in our study, their characteristics being summarized in table 1

Results

In 90,4% (19/21) of the tests conducted, the TMI, whether free from any bony attachment or screwed to the orbital rim, has tended to move inwardly in the orbit, and / or to deform in a "blow-in" motion (figure 3). In 19 % (4/21) a fracture of the inferior orbital rim was associated, allowing the bone-plate complex to move and/or deform. In 39,1% (9/23) the movement and/or deformation of the TMI was allowed by partial or total failure of the osteosynthesis. An associated fracture of the lamina papyracea was encountered in 19 % (4/21) of the tests. The results are detailed in table 1.

Discussion

Our simulations showed that under the stress of blunt orbital traumas, TIM used to reconstruct floor fractures may distort and threaten the orbital content.

Finite element model has proven to be a valuable tool to determine the most convenient location, design and material to use for fracture fixation devices [4,5]. Experimentations on an empty orbit with a simplified titanium plate induced in 80% (12/15) of cases a total or partial rupture of fixation between the plate and the bone eventually with fracture next to the screws. In the 3 cases in which this fixation remained intact, the plate itself showed a vertical displacement of up to 3.65 mm. With a filled orbit (fat and simplified eyeball), the findings were similar, but with lower displacement amplitudes. In this case, no fracture of the orbital rim screwing was found, possibly due to amortization and redistribution of forces by the intraorbital fat [6]. These results are consistent with our clinical findings [1]: a TMI submitted to a direct trauma is likely to deform the orbit inwardly (in a "blow-in" motion) and to threaten the orbital contents, including the eyeball.

However, several limitations must be pointed out. Even in the tests conducted with a perforated TMI, the shape of our titanium plate was simplified, and didn't faithfully reproduce a 3D TMI. The fixation of the TMI to the bone was also an approximation of a real cortical screwing. Rather than modeling a real screw, we numerically attached the nodes of the plate with those of the bone. Nevertheless, this approximation seems acceptable to us. In 4 of our tests, the bone fractured on contact with the attached nodes, as it sometimes happens in vivo, when a screwed osteosynthesis plate is pulled apart, fracturing the cortical bone next to one or several screws. Partial or total failure of osteosynthesis (i.e. the link between two nodes) occurred in 9 other tests. Kasrai et al [7] demonstrated, in a biomechanical analysis of an orbitozygomatic titanium osteosynthesis in human cadavers, sharing strains at the level of bony buttresses, able to create screwing failures. They also noticed a significant decreases in the force required to induce a fracture following titanium plate fixation, and identified plate deformation as a primary cause of failure under blunt trauma load conditions.

The absence of detailed anatomy of the ethmoid was another limit of our orbit FEM. Ramesh et al [8] proved that ethmoidectomy on post mortem human subject reduces the impact energy necessary to induce orbital fractures and increases the prevalence of the medial wall involvement. In our study, we aimed to reproduce a straight punch to the face, and therefore we favored traumas targeting the inferior orbital rim, consistent with the historical buckling theory of orbital fractures [9]. In this theory, the fractures of the orbital floor are usually anterior, of a rather small surface, and rarely reach the medial wall. However, a fracture of the medial wall of the orbit occurred in 4 of our tests, 3 of which with a filled orbit. Actual trends are that hydraulic and buckling theories of orbital fracture coexist and may result in similar fracture patterns [10,11]. Forces transmission through the intraorbital fat may have favored lamina papyracea fractures, according to hydraulic theory. Another hypothesis is that the TMI is stiffer than the bone of the orbital floor, therefore the forces are transmitted more posteriorly into the TMI reconstructed orbit than into the native orbit.

TMI have proved their effectiveness for orbital fractures reconstruction [12], even in complex cases. Specific complications, such as infections and adherence syndromes are rare [13,14]. This could explain maxillofacial surgeons' craze for these implants.

In contrast, complications related to TMI in case of traumatic recurrence have been studied very little. Maxillofacial trauma recurrence is anything but anecdotal. Nygaard et al [15] demonstrated that recidivism for interpersonal violence results in a significant number of admissions to trauma centers. In their cohort, almost 10% of patients were recidivists. These patients had a higher proportion of blunt assault lesions than non-recidivists. It is crucial that the initial interrogation insists on the past trauma history of patients. In the McCoy's study [16] the recidivism rate was up to 29.3%. The highest rates were noted in victims of interpersonal violence. Alcohol and drug abuses are both well-documented risk factors of trauma recidivism and are frequently encountered in maxillofacial trauma population [17]. The removal of osteosynthesis material is usually proposed for most maxillofacial fractures (mandibles, zygoma etc.) after bone consolidation, but not for orbital fractures. The risk of deformation of the material persists long term, theoretically for the patient's lifetime.

In line with already reported clinical observations [1], our finite element analysis tends to demonstrate that, in the event of traumatic recurrence, a TMI may deform, and therefore turn into a potentially threatening penetrating object for the intra-orbital structures. Further studies and improvements to our FEM are required to confirm this conclusion. Taking into account the complications of TMIs in case of traumatic recurrence opens new research perspectives, and could lead to reconsider the indications of these implants. Finite element analysis could also help to modify and to improve the design of TMIs, so as to prevent a blow-in distortion in case of trauma recurrence.

Bibliography

1. Foletti JM, Scolozzi P. Severe distortion of an orbital titanium mesh implant after recurrent facial trauma: a potential threat to the orbital contents? Br J Oral Maxillofac Surg. 2017;55:836-838
2. Foletti JM, Martinez V, Graillon N, Godio-Raboutet Y, Thollon L, Guyot L. Development and validation of an optimized finite element model of the human orbit. J Stomatol Oral Maxillofac Surg. 2018 Oct 1. pii: S2468-7855(18)30186-1
3. Whiting WC, Gregor RJ, Finerman GA. Kinematic analysis of human upper extremity movements in boxing. Am J Sports Med. 1988;16:130-136
4. Al-Sukhun J, Lindqvist C, Kontio R. Modelling of orbital deformation using finite-element analysis. J R Soc Interface. 2006 22;3:255-262
5. Al-sukhun J, Penttilä H, Ashammakhi N. Orbital stress analysis, part V: systematic approach to validate a finite element model of a human orbit. J Craniofac Surg. 2012;23:669-674
6. Schoemaker I, Hoefnagel PP, Mastenbroek TJ, Kolff CF, Schutte S, van der Helm FC, Picken SJ, Gerritsen AF, Wielopolski PA, Spekreijse H, Simonsz HJ. Elasticity, viscosity, and deformation of orbital fat. Invest Ophthalmol Vis Sci. 2006;47:4819-4826
7. Kasrai L, Hearn T, Gur E, Forrest CR. A biomechanical analysis of the orbitozygomatic complex in human cadavers: examination of load sharing and failure patterns following fixation with titanium and bioresorbable plating systems. J Craniofac Surg. 1999 ;10:237-43
8. Ramesh S, Bokman C, Mustak H, Lo C, Goldberg R, Rootman D. Medial Buttressing in Orbital Blowout Fractures. Ophthalmic PlastReconstr Surg. 2018;12

9. Le Fort R. Etude experimentale sur les fractures de la machoire superieure. Rev Chir Paris 1901;23:208–479

10. Ahmad F, Kirkpatrick NA, Lyne J, Urdang M, Waterhouse N. Buckling and hydraulic mechanisms in orbital blowout fractures: fact or fiction? J Craniofac Surg. 2006;17:438-441

11. Patel S, Andrecovich C, Silverman M, Zhang L, Shkoukani M. Biomechanic Factors Associated With Orbital Floor Fractures. JAMA Facial Plast Surg. 2017 ;19:298-302

12. Ellis E 3rd, Tan Y. Assessment of internal orbital reconstructions for pure blowout fractures: cranial bone grafts versus titanium mesh. J Oral Maxillofac Surg. 2003;61:442-53

13. Peng MY, Merbs SL, Grant MP, Mahoney NR. Orbital fracture repair outcomes with preformed titanium mesh implants and comparison to porous polyethylene coated titanium sheets. J Craniomaxillofac Surg. 2017;45:271-274

14. Kersey TL, Ng SG, Rosser P, Sloan B, Hart R. Orbital adherence with titanium mesh floor: a review of 10 cases. Orbit. 2013;32:8-11

15. Nygaard RM, Marek AP, Daly SR, Van Camp JM. Violent trauma recidivism: Does all violence escalate? Eur J Trauma Emerg Surg. 2017;22

16. McCoy AM, Como JJ, Greene G, Laskey SL, Claridge JA. A novel prospective approach to evaluate trauma recidivism: the concept of the past trauma history. J Trauma Acute Care Surg. 2013;75:116-21

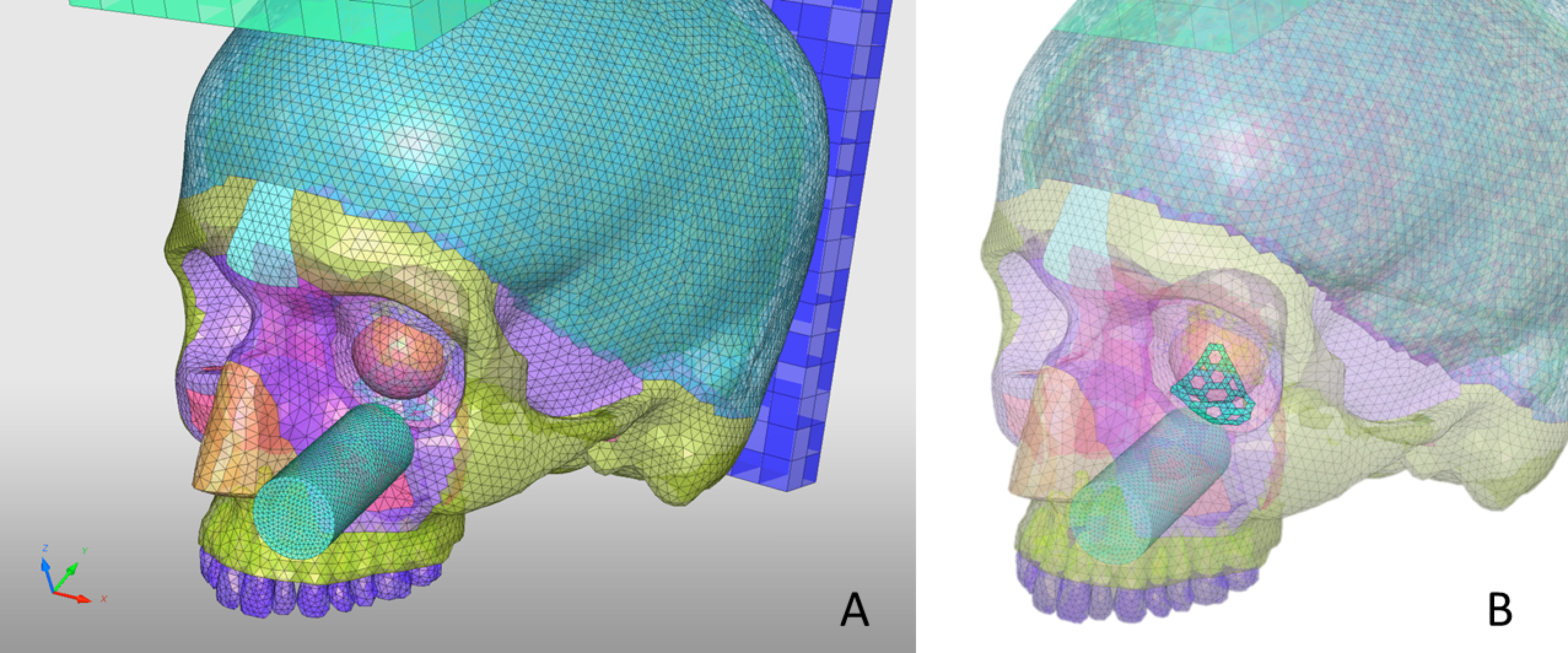
17. Foletti JM, Bruneau S, Farisse J, Thiery G, Chossegros C, Guyot L. Screening for psychiatric risk factors in a facial trauma patients. Validating a questionnaire. Rev Stomatol Chir Maxillofac Chir Orale. 2014;115:343-8

Figure captions

Figure 1 – 3D view of the finite element model of the human orbit used for blunt trauma tests. Transparency levels highlight the orbit filled with fat and the eyeball (A), as well as the simplified titanium mesh implant used to reconstruct the orbital floor (B). Notice the metallic cylinder impactor utilized to hit the inferior orbital rim.

Figure 2 – Detailed view of the fracture and the TMI used to rebuild it. Notice that the TMI is transparent, with clear blue lines, to show the fracture that it covers.

Figure 3 – Results of a crash simulation under Hypercrash software. The inferior orbital rim was impacted with a 300g metallic cylinder at 7m/s. Besides the resulting fracture, the simplified TMI used to reconstruct the orbital floor tended to move vertically, this displacement being indicated by the pink silhouette of the titanium plate (A), and visible *a posteriori* (B).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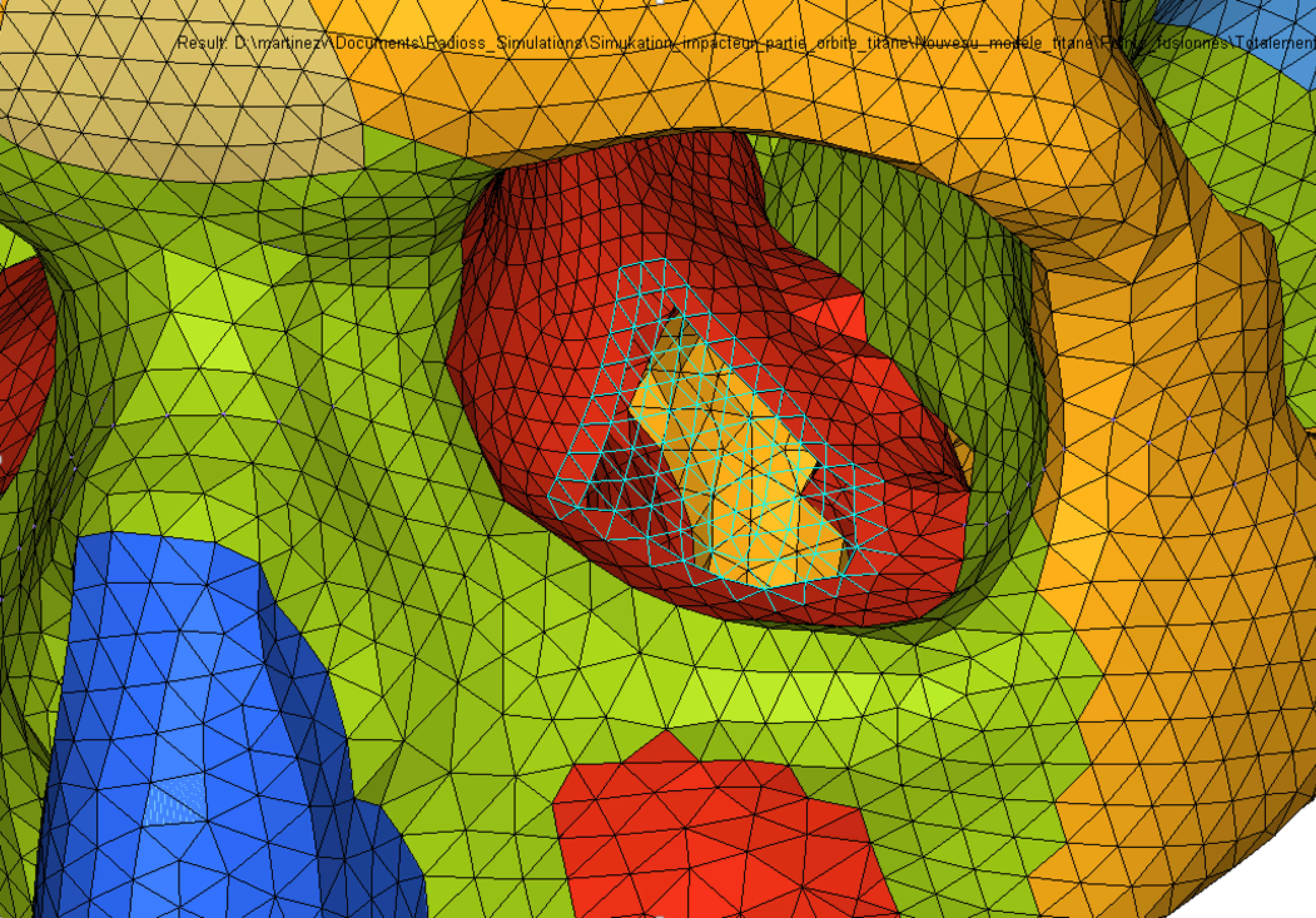
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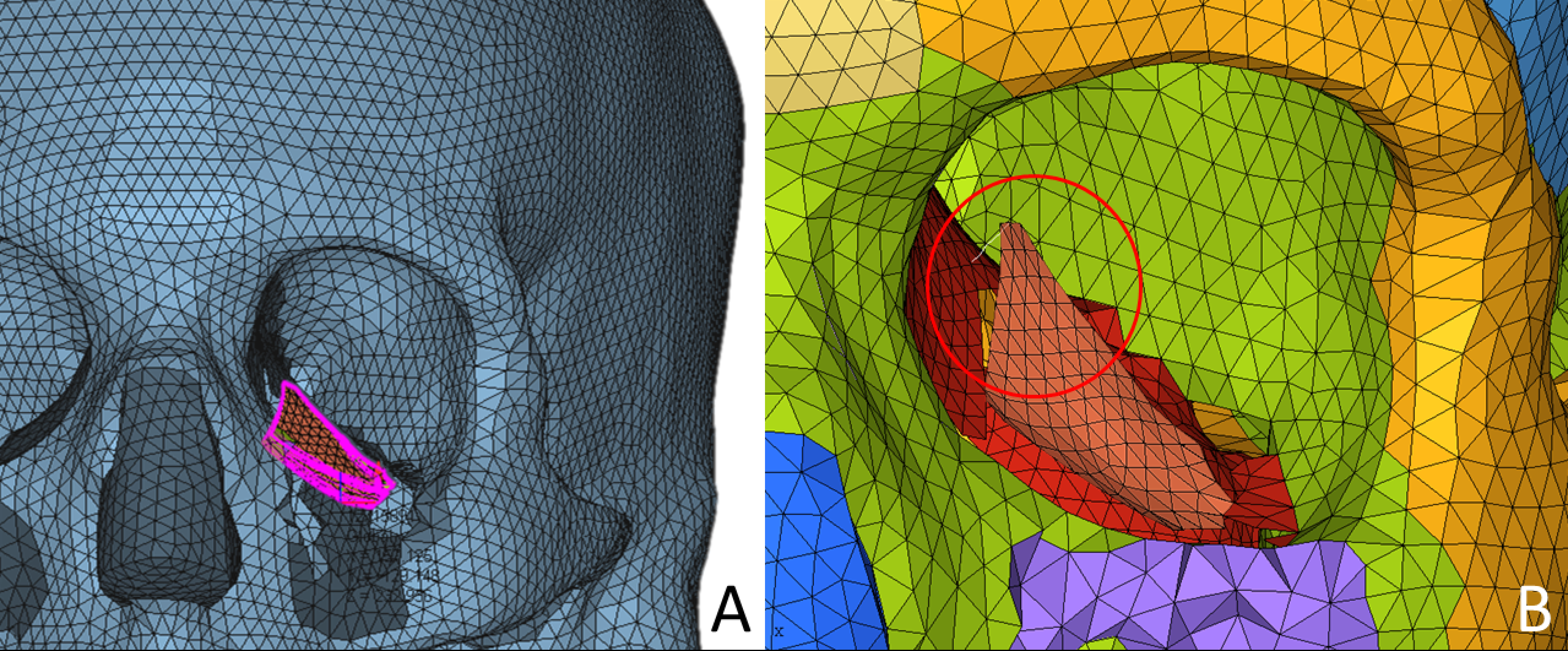
A
B

Test	Orbit status	Orbital floor status	TMI status	Acceleration (m/s)	weight (g)	results
1	EO	Simplified TMI	Anterior fixation	6	300	The osteosynthesis resists; the plate is deformed and moves about 1 mm vertically
2	EO	Simplified TMI	Anterior fixation	6	500	The osteosynthesis resists; fracture close to the screws and mobility of the bone-plate complex upwards (10,7mm) and backwards (9,5mm)
3	EO	Simplified TMI	Anterior fixation	7	300	Partial failure of the osteosynthesis; mobility of the plate upwards and backwards, with about 10 degrees of sagittal rotation
4	EO	Simplified TMI	2 points fixation	6	300	The osteosynthesis resists; fracture close to the screws and mobility of the bone-plate complex upwards (3,6mm)
5	EO	Simplified TMI	2 points fixation	6	500	the osteosynthesis resists ; fracture close to the screws and mobility of the bone-plate complex upwards (9,2mm)
6	EO	Simplified TMI	2 points fixation	7	300	the osteosynthesis resists ; fracture close to the screws and mobility of the bone-plate complex upwards (>20mm)
7	EO	Simplified TMI	External fixation	6	300	Partial failure of the osteosynthesis; mobility of the plate upwards (8mm), with about 40 degrees of external sagittal rotation
8	EO	Simplified TMI	External fixation	6	500	Total failure of the osteosynthesis; mobility of the plate upwards (9mm), with about 25 degrees of external sagittal rotation
9	EO	Simplified TMI	External fixation	7	300	Total failure of the osteosynthesis; mobility of the plate upwards (10mm) and externally (3mm)
10	EO	Simplified TMI	Internal fixation	6	300	Total failure of the osteosynthesis; mobility of the plate upwards (4,6mm), with about 15 degrees of internal sagittal rotation
11	EO	Simplified TMI	Internal fixation	6	500	Total failure of the osteosynthesis; mobility of the plate upwards and backwards (>20mm), with about 10 degrees of internal sagittal rotation
12	EO	Simplified TMI	Internal fixation	7	300	Total failure of the osteosynthesis; mobility of the plate upwards (10,5mm) and backwards (>20mm), with about 20 degrees of internal sagittal rotation
13	EO	Simplified TMI / perforated	Anterior fixation	6	300	The osteosynthesis resists; the plate is deformed and moves about 0,8 mm vertically
14	EO	Simplified TMI / perforated	Anterior fixation	6	500	The osteosynthesis resists; the plate is deformed and moves about 0,95 mm vertically
15	EO	Simplified TMI / perforated	Anterior fixation	7	300	Partial failure of the osteosynthesis; the plate is deformed and moves upwards (2,65mm); lamina papyracea is fractured
16	FO fat eyeball	Simplified TMI / perforated	None	6	300	The plate is deformed and moves about 0,34 mm vertically
17	FO fat eyeball	Simplified TMI / perforated	None	6	500	The plate is deformed and moves about 0,44 mm vertically
18	FO fat eyeball	Simplified TMI / perforated	None	7	300	The plate is deformed and moves about 1mm vertically; lamina papyracea is fractured

19	FO fat eyeball	Simplified TMI / perforated	Anterior fixation	6	300	The plate is not deformed.
20	FO fat eyeball	Simplified TMI / perforated	Anterior fixation	6	500	The plate is not deformed. Lamina papyracea is fractured.
21	FO fat eyeball	Simplified TMI / perforated	Anterior fixation	7	300	Partial failure of the osteosynthesis; the plate is deformed and moves about 0.21 mm vertically; lamina papyracea is fractured

Table 1 – Summary of the characteristics and results of the 21 simulations of blunt trauma performed on a 3D finite element model of the human orbit. The orbit status (empty EO *versus* filled with fat and the eyeball FO), the orbital floor status (reconstructed by a titanium mesh implant TMI perforated or not), the eventual screwing of the TMI (if present), the impactor's speed and mass are precised for each of the tests.