UNESP - Universidade Estadual Paulista

“Júlio de Mesquita Filho”

Faculdade de Odontologia de Araraquara

Lucas Borin Moura

Avaliação tomográfica de fraturas orbitárias unilaterais tratadas por meio de malhas de titânio e validação da fisiopatologia do trauma orbitário por meio de elementos finitos

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RESUMO

Fraturas orbitárias apresentam alta prevalência, ocasionando alterações estéticas e funcionais com repercussão clínica. A severidade dos defeitos orbitários é dependente da sua extensão, morfologia e localização, sendo que as alterações do volume orbitário estão intimamente relacionadas com a presença de enoftalmia e de diplopia. Desta forma, o tratamento objetiva restabelecer a anatomia e o volume orbitário prévio ao trauma. Atualmente, o material mais utilizado para a reconstrução orbitária é a malha de titânio convencional, sendo que a combinação de outras técnicas, como assistência por endoscopia e utilização de biomodelos, pode otimizar o tratamento. Em relação à fisiopatologia do trauma orbitário, dois mecanismos estão historicamente estabelecidos, mecanismo hidráulico e trauma direto ao rebordo orbitário. Entretanto, o completo entendimento das características da distribuição de forças de cada mecanismo ainda não está esclarecido. Desta forma, este trabalho teve o objetivo de realizar uma análise tomográfica de fraturas orbitárias unilaterais tratadas por meio de malhas de titânio convencionais; confeccionar um modelo digital da cavidade orbitária para a simulação dinâmica dos mecanismos de trauma orbital; e reportar a otimização do tratamento de fraturas orbitárias pela associação de técnicas com endoscopia transantral e biomodelos.

Palavras-chave: Órbita. Fraturas orbitárias. Telas cirúrgicas. Análise de elementos finitos. Simulação por computador.

Moura LB. Tomographic evaluation of unilateral orbital fractures treated using titanium mesh and validation of orbital trauma pathophysiology by finite element analysis [Tese de Doutorado]. Araraquara: Faculdade de Odontologia da UNESP; 2018.

ABSTRACT

Orbital fractures are high prevalent, and result in aesthetic and functional impairments. The severity of orbital defects is related with the extension, morphology and location. The orbital volume changes are intimately associated with the presence of enophthalmos and diplopia. Therefore, the treatment must reestablish the orbital anatomy and volume. Presently, the most applied material for orbital reconstruction is the conventional titanium mesh, and the association of other techniques, such as endoscopic assistance and the use of printed models, can optimize the treatment. About the orbital trauma pathophysiology, two mechanisms are historically established – hydraulic and buckling mechanisms. However, the complete understanding of the features of stress distribution of each mechanism are not clear. Thus, the aim of this work is to perform a tomographic evaluation of unilateral orbital fractures treated with conventional titanium mesh; to create a digital model of the orbital cavity for a dynamic simulation of the mechanisms of orbital trauma; and to report the optimization of treatment of orbital fractures by the association of techniques, with transantral endoscopy and printed model.

Key-words: Orbit. Orbital fractures. Surgical mesh. Finite element analysis. Computer simulation.

SUMÁRIO

1 INTRODUÇÃO

A cavidade orbitária é uma estrutura piramidal bilateral localizada na região de terço médio facial, que apresenta como função a contenção do aparelho lacrimal, do globo ocular e de suas estruturas adjacentes, como músculos, nervos e vasos. Anatomicamente sete ossos são responsáveis pela composição das paredes orbitárias, sendo a parede superior formada pelos ossos frontal e esfenoide; a parede medial pelos ossos etmoide, esfenoide, lacrimal e maxila; a parede inferior ou assoalho da órbita pela maxila, zigomático e palatino; e a parede lateral por zigomático e esfenoide[1]. Este conjunto de paredes delimita o volume orbitário permitindo a correta posição e projeção do globo ocular[2].

Os traumatismos faciais na região orbitária podem gerar fraturas destas paredes com consequentes defeitos ósseos e alterações clínicas. Em geral, eles são verificados em associação à fratura do complexo zigomático-orbitário, fraturas complexas da face ou, ainda, como fraturas isoladas de blow-out ou blow-in[3]. Estes defeitos acarretam em alterações do volume do continente orbital devido à expansão da cavidade orbitária ou sua redução[4]. As fraturas orbitárias representam mais de 40% das fraturas de terço médio facial[5, 6], e essa alta prevalência está relacionada com as características anatômicas da órbita e a presença de paredes ósseas finas, que aumentam a suscetibilidade aos traumatismos e, consequentemente, às fraturas[1].

O primeiro relato de uma fratura isolada de parede orbitária foi descrito por Smith, Regan[7], em 1957, no qual foi apresentado um caso de deslocamento do assoalho orbital para o interior do seio maxilar sem a presença de fratura do rebordo infraorbitário, este tipo de fratura foi denominado como blow-out[4, 7]. Basicamente, existem dois mecanismos que podem explicar esta injúria, primeiramente esta fratura pode ocorrer devido a um impacto direto sobre o rebordo orbitário, o qual é transmitido para a parede orbital adjacente gerando a fratura. Mas também, esta fratura pode ocorrer devido a um mecanismo hidráulico, em que é observado um trauma direito sobre o globo ocular gerando um aumento abrupto da pressão interna da órbita, provocando assim, o contato das estruturas orbitárias com a parede orbital e causando a fratura[8, 9].

Ainda, Dingman, Natvig[10] descreveram a fratura conhecida como blow-in. Os autores apresentaram um caso de trauma na região de seio maxilar, que por meio de um mecanismo de pressão pneumática, gerou aumento da pressão do interior do seio e deslocou superiormente o assoalho orbitário para o interior da órbita, não afetando o rebordo infraorbitário[4, 10].

O assoalho orbitário e a parede medial são as regiões mais frequentemente lesadas[8], sendo que as fraturas combinadas destas regiões ocorrem mais comumente do que a fratura isolada das paredes orbitárias, e causam um comprometimento da estrutura ínfero-medial na junção etmoide-maxilar promovendo um aumento do volume orbitário[11]. Já a parede lateral é dependente da fratura do complexo zigomático e a sua reconstrução está relacionada ao correto reposicionamento anatômico deste complexo[9].

As fraturas das paredes orbitais podem apresentar defeitos com uma variedade de morfologias e extensão, que estão relacionados ao mecanismo e à força do traumatismo. Conforme descrito, dois mecanismos clássicos da fisiopatologia do trauma orbitário são reportados na literatura: mecanismo hidráulico e trauma direto ao rebordo orbitário. O primeiro está associado a um traumatismo ao globo ocular e aumento da pressão interna da cavidade orbitária resultando na sua fratura, o segundo está relacionado ao trauma direto sobre o osso e à propagação de forças sobre as paredes orbitárias[9]. Embora estes mecanismos estejam historicamente estabelecidos, eles continuam sendo tópicos de discussão na literatura[12]. Estudos em cadáveres descrevem que a força necessária para ocasionar fratura por meio do mecanismo hidráulico é dez vezes maior do que a força necessária pelo mecanismo de trauma direto ao rebordo. Ainda, o padrão de fratura é dependente do tipo da mecânica do trauma, sendo que o trauma direto ao rebordo resulta em fraturas nas regiões anterior e média do assoalho orbitário, sem o envolvimento da parede medial ou herniação de tecidos moles. Enquanto que fraturas decorrentes do mecanismo hidráulico podem se estender para a região posterior e parede medial, e frequentemente estão associadas com herniação de tecido mole para dentro do seio maxilar[13]. Atualmente, para melhor entendimento dos mecanismos de trauma e padrão de fraturas, tem-se lançado mão de simulações de traumatismos em modelos digitais pela análise tridimensional por meio de elementos finitos[12, 14, 15].

Nagasao et al.[15] realizaram estudo em elementos finitos sobre o padrão de fraturas de acordo com a localização e distribuição de forças. Os autores confeccionaram dez modelos por CAD a partir do escaneamento de crânios secos e verificaram quatro padrões de trauma: (A) força de 1,2J sobre o globo ocular –

mecanismo hidráulico; (B) força de 0,8J sobre o globo ocular e 0,4J sobre o rebordo infraorbitário; (C) força de 0,8J sobre o rebordo infraorbitário e 0,4J sobre o globo ocular; (D) força de 1,2J sobre o rebordo infraorbitário – mecanismo de trauma direto. Os autores verificaram que os padrões A e B resultaram em regiões de stress menores localizadas na parede medial, e que os padrões C e D resultaram em forças de stress no assoalho orbitário e região ínfero-medial de órbita, sendo que o padrão C apresentou a maior área de stress para fratura.

Schaller et al.[12], a partir dos exames tomográficos de um paciente hígido, segmentaram o esqueleto facial e incluíram um globo ocular artificial (em contato com as paredes orbitárias) para simulação de trauma orbitário. Os autores simularam o impacto de um peso de cobre sobre globo ocular, rebordo infraorbitário e a combinação destes sítios. Foi verificado que o mecanismo hidráulico concentrou forças sobre a região anterior e ínfero-medial da órbita, o trauma ao rebordo orbitário resultou em forças de stress na região posterior do assoalho orbitário, a combinação de traumas na região ínfero-medial de órbita, em terço médio anteroposterior.

Desta forma, o completo entendimento da biomecânica das fraturas orbitárias não está esclarecido, embora, a ação dos mecanismos de pressão hidráulica e trauma direto ao rebordo orbitário sobre o tecido ósseo estejam bem definidos[12-15]. Não há estudos que avaliem a estrutura orbitária como um todo, incluindo os tecidos muscular, adiposo e globo ocular.

A avaliação da severidade de um traumatismo orbitário dependerá dos seguintes fatores: o tamanho do defeito, a sua localização, o número de paredes envolvidas e a dificuldade técnica para a reconstrução. Defeitos pequenos, localizados na região anterior do assoalho orbitário, apresentam pouca influência na posição do globo ocular e na sintomatologia. Porém, defeitos com comprometimento da região póstero-medial, geram um aumento do continente orbitário resultando em enoftalmia e diplopia[3, 16]. Defeitos ósseos que envolvam todo o assoalho orbitário, compreendendo a fissura orbitária inferior e/ou região posterior de órbita, representam um desafio para o tratamento, pois os acessos cirúrgicos devem expor as margens não envolvidas do defeito ósseo, a fim de estabilizar os materiais de reconstrução[3].

O tratamento das fraturas orbitárias envolve o restabelecimento estético e funcional, a reconstrução da cavidade orbitária deve restaurar o volume e a anatomia orbitária[1, 5, 17, 18], sendo que a simetria orbitária não deve ser reestruturada em apenas um plano facial, devendo incluir a posição do globo ocular, a redução das fraturas ósseas e a correção dos tecidos moles, como a musculatura extraocular e o ligamento cantal[19-21]. Outros fatores relacionados às dificuldades técnicas da reconstrução orbitária são a necessidade de acessos cutâneos que podem gerar cicatrizes e a atrofia da gordura e da musculatura orbitária, que podem necessitar de correções secundárias tardiamente[18, 20, 22].

É importante observar que mesmo após o tratamento destas lesões, uma alta e variável porcentagem de sequelas e complicações são encontradas, podendo destacar: a diplopia, a enoftalmia persistente e a hipoestesia de nervo infraorbitário[23].

A hipoestesia do nervo infraorbitário está relacionada com a lesão direta ao nervo devido ao traumatismo, ou indiretamente devido ao deslocamento da fratura, estando presente entre 7% e 59% dos casos de fratura orbitária[24].

As alterações no volume orbitário e nos tecidos moles, após traumatismo ou correção cirúrgica, podem gerar enoftalmia e diplopia[2, 18]. Os mecanismos que resultam nestas alterações incluem a perda do suporte dos ligamentos, contratura cicatricial, atrofia de gordura orbitária, herniação dos tecidos moles para o seio maxilar e o aumento do volume orbitário ósseo[25].

A diplopia está relacionada com a presença de enoftalmia e ocorre devido a uma posição inadequada do globo ocular, ao volume orbitário alterado ou a um aprisionamento da musculatura ocular. Como consequência, ocorre um distúrbio na mobilidade ocular gerando a visualização de imagens duplicadas[3, 8, 20]. Ela é observada entre 20% e 42,5% das fraturas isoladas de assoalho orbital e acima de 86% das fraturas complexas envolvendo múltiplas paredes ou o terço posterior do assoalho orbital[24].

A enoftalmia ocorre entre 7% e 27,5% das fraturas orbitárias, devido à alteração da relação entre o volume orbitário e o seu conteúdo, ocorrendo o afundamento do globo ocular em sua projeção anteroposterior, por conseguinte a presença de enoftalmia acarretará diplopia[24, 26]. É verificado que o aumento do volume orbitário apresenta uma maior correlação com a presença de enoftalmia do que as alterações no tecido adiposo orbitário[5, 25]. Logo, na reconstrução primária, o cirurgião tem o papel de restaurar a forma (volume) e função orbitária adequadamente, caso contrário, o alargamento e a deformação poderão resultar em enoftalmia e diplopia[19, 20]. Sabe-se que a cada centímetro cúbico aumentado resulta em 0,89mm de enoftalmia[8, 27].

A correção cirúrgica de enoftalmia é um desafio clínico, visto que resultados satisfatórios são encontrados em apenas 50% a 58% dos pacientes[8, 28]. Além das dificuldades técnicas e de reconstrução dos tecidos ósseo e mole, observa-se que em pacientes não-traumatizados existe uma diferença entre os volumes orbitários entre 7% e 8%[29, 30].

Conforme descrito previamente, os defeitos orbitários resultam em alterações volumétricas comumente relacionadas com o aumento da cavidade orbitária[3, 8, 11, 16, 19, 27, 31, 32]. Devido a importância do volume orbitário no desenvolvimento destas alterações clínicas, as alterações volumétricas são foco de constante análise na literatura. O primeiro estudo que analisou a influência do volume orbitário sobre a severidade do enoftalmo foi realizado por Bite et al.[33] em 1985. Os autores compararam, por meio de tomografia computadorizada, a órbita íntegra e fraturada quanto ao volume dos componentes orbitários e verificaram uma relação positiva entre o aumento do volume orbitário com o enoftalmo, sendo que o volume das demais estruturas orbitárias foi semelhante entre as órbitas[33].

Tahernia et al.[9] avaliaram os exames tomográficos pré-operatórios de 45 pacientes portadores de fraturas isoladas do assoalho orbitário e verificaram um aumento médio do volume orbitário de 28,3%. Os autores concluíram que um aumento de 20% do volume orbitário é um parâmetro tomográfico que indica a necessidade de intervenção cirúrgica.

Oh et al.[17] verificaram as alterações volumétricas da cavidade orbitária em fraturas isoladas de órbita. Os autores avaliaram três grupos de acordo com a localização das fraturas: (A) assoalho orbitário, (B) assoalho e parede medial e (C) parede medial. Verificaram que o maior aumento volumétrico pré-operatório ocorreu no grupo B, seguido pelo A e C. Após o tratamento cirúrgico todos os grupos apresentaram diminuição do volume orbitário, entretanto a órbita reconstruída permaneceu aumentada em relação à íntegra. Ainda, os autores realizaram avaliação da posição do globo ocular por meio de exoftalmômetro de Hertel, entretanto sem diferenças significativas entre os dois períodos.

Kim et al.[34] compararam o volume orbitário em 44 pacientes portadores de fraturas orbitárias tratadas por meio de implantes de polietileno poroso associados ou não com malhas de titânio. Os autores verificaram que ambos materiais foram efetivos para o reparo dos defeitos ósseos.

Jin et al.[35] avaliaram a relação entre a extensão do defeito ósseo e o grau de enoftalmia em pacientes portadores de fraturas de parede medial de órbita. Os autores analisaram os exames tomográficos pré-operatórios de nove pacientes, e verificaram que a cada 0,9 cm^3 de tecido herniado resultou em 2 mm de enoftalmo. Concluíram assim, que um aumento do volume orbitário em 0,9 cm^3 é um fator indicativo de tratamento cirúrgico.

Han et al.[36] analisaram os desfechos de fraturas de assoalho orbitário e/ou parede medial tratadas por acesso subciliar ou pela associação de acesso subciliar e transcaruncular. Os autores não identificaram diferenças entre o tempo cirúrgico, complicações e reestabelecimento do volume orbitário entre os dois acessos. Assim, concluíram que o reestabelecimento do volume orbitário é independente do acesso cirúrgico utilizado, desde que o mesmo tenha indicação.

Zavattero et al.[37] compararam 30 fraturas orbitárias tratadas com auxílio de navegação intraoperatória e 25 fraturas tratadas convencionalmente. Como resultado, observaram que a redução do volume orbitário foi alcançada no grupo com auxílio de navegação, enquanto que o grupo tratado pelo método convencional não restabeleceu o volume adequadamente. Os autores concluíram que a navegação transoperatória é um método viável para otimização do tratamento de fraturas orbitárias. Entretanto, a navegação intraoperatória não se encontra difundida globalmente nos centros cirúrgicos, sendo o tratamento convencional o mais utilizado mundialmente para a reconstrução orbitária, em geral por meio do conhecimento anatômico da cavidade orbitária e malhas de titânio[38, 39].

Para diagnóstico, avaliação e planejamento cirúrgico das fraturas orbitárias, o exame de escolha é a tomografia computadorizada, pois disponibiliza detalhada informação sobre tamanho, localização e severidade dos defeitos, além de permitir a visualização do aprisionamento de tecidos moles[8, 20, 23]. Para tratamento, inúmeros materiais e tecnologias podem ser utilizados, incluindo modelos estereolitográficos, implantes pré-fabricados de titânio/biocerâmicas por meio de CAD/CAM, técnica de espelhamento e impressão tridimensional e navegação intraoperatória[19, 21]. Entretanto, a malha de titânio convencional ainda é o material mais utilizado para a reconstrução orbitária, devido ao seu custo e disponibilidade. Desta forma, necessita-se que o cirurgião tenha a capacidade de reconstruir adequadamente a anatomia/volume orbitário baseado nos conceitos cirúrgicos já bem descritos na literatura[38, 39].

Portanto, devido à complexidade do tratamento de fraturas orbitárias e à alta prevalência de complicações decorrentes da alteração anatômica, este estudo objetivou avaliar o volume orbitário e a posição anteroposterior do globo ocular após o tratamento de fraturas unilaterais por meio de malhas de titânio; validar a fisiopatologia destas lesões em um modelo digital que compreenda todos os tecidos envolvidos; e reportar a otimização do tratamento de fraturas orbitários pela associação de técnicas com endoscopia transantral e biomodelos.

2 PROPOSIÇÃO

O presente estudo teve por objetivo:

Artigo 1 – Avaliar, por meio de tomografias computadorizadas, o volume e a posição anteroposterior do globo ocular em fraturas orbitárias unilaterais tratadas por meio de malha de titânio;

Artigo 2 – Confeccionar um modelo digital da cavidade orbitária e realizar a simulação dinâmica dos mecanismos de trauma orbitário;

Artigos 3 e 4 – Reportar a otimização do tratamento de fraturas orbitárias pela associação de técnicas com endoscopia transantral e biomodelos.

3 ARTIGO 1 – Tomographic evaluation of unilateral orbital fractures treated by titanium mesh*

Volumetric evaluation of orbital fractures treated by titanium mesh

Short title: Volumetric evaluation of orbital fractures

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Abstract

This study aims to evaluate orbital volume and anteroposterior eyeball position in orbital fractures treated by titanium mesh. This multicenter study evaluated 60 postoperative CT scans of unilateral orbital fractures treated using titanium mesh. Orbital defects were classified according to the extension and involved regions, and the orbital volumes were analyzed by two methods, image sectioning (IS) and computerized segmentation (CS). The eyeball position was obtained from the axial slice in the mid orbit region. Differences up to 8.0% (volume) and 2.0 mm (eyeball position) were considered normal. Most of defects were class II (n=25) and class III (n=26). Volumetric differences between unaffected and reconstructed orbit ranged from -7.15% to 10.46% (mean: -0.15%), and from -6.32% to 9.69% (mean: -0.01%) in IS and CS method, respectively. In both methods, two reconstructions were greater than anatomical differences, however there was no statistical differences between the orbits in both methods, IS (p=0.852) and CS (p=0.987). Anteroposterior eyeball position ranged from -0.9 mm to 1.8 mm. The correlation between defect classification, eyeball position and IS or CS, were not positive. In conclusion, regardless of the extent of the orbital defect or evaluation method, fractures treated by titanium mesh reestablished adequately the orbital volume.

Key-words: Orbit; Orbital fractures; Surgical mesh.

Introduction

Orbital fractures are common and its prevalence exceeds 40% of the midface fractures[1-3]. The most involved regions are the orbital floor and the medial wall, in combination or isolated[4]. The associated defects lead to orbital volume changes, due to expansion or reduction of the orbital cavity[5], and its morphology and extension are determined by force and mechanism of injury. The severity of an orbital defect depends of its size, location, number of involved walls, and technical difficult to treatment[6, 7].

The presence of orbital defects and consequent orbital volume enlargement lead to clinical symptoms, particularly diplopia and enophthalmos due to incorrect eyeball position[4, 8-11]. Consequently, the treatment must restore the orbital volume and anatomy, based in the tridimensional position of bones, eyeball and soft tissues[2, 12-15].

Nowadays, there are several technologies to improve orbital reconstruction, including: pre-bended implants; stereolithographic models; CAD/CAM customized implants; and intraoperative navigation systems[14, 16]. However, those resources present considerable cost, learning curve, and are not available as a routine in most of hospital centers. Thus, standard titanium mesh is widely used, and the surgeon need to be able to adequately reconstruct orbital volume and anatomy based in surgical concepts[17, 18].

Therefore, due to the complexity of the orbital reconstruction, the aim of this study was to perform a tomographic evaluation of orbital fractures treated using standard titanium mesh, and compare two methods of volumetric analysis.

Materials and Method

The present retrospective multicenter study was approved by the Research Ethics Committee of the School of Dentistry of Araraquara – São Paulo State University, Brazil (CAAE: 44029115.9.0000.5416) and followed the STROCSS statement[19] (Strengthening the Reporting of Cohort Studies in Surgery).

CT scan of patients with unilateral orbital fractures from the department of Diagnosis and Surgery, School of Dentistry, São Paulo State University (Unesp), Brazil, and from the department of Cranio-maxillofacial Surgery, University Hospital Basel, Switzerland, were screened from medical records.

The adopted inclusion criteria were: unilateral and isolated orbital fractures; treated by standard titanium mesh; treated using subciliary and/or coronal approaches; with a six-month postoperative CT scan. Patients with presence of bilateral orbital fractures; combined facial fractures; syndromic; history of previous orbital trauma or surgery; and treated with customized/pre-bended titanium mesh or bone grafts were excluded.

CT scan evaluation

The analyzed CT scans were volumetric, obtained in the late postoperative period (six months after treatment), and stored according to the DICOM protocol on a 14-bit gray scale with a 0.25mm (voxel size) resolution, thereby allowing the different analyses.

The orbital defects were classified according to the number of involved walls and by Jaquiery et al[7] (2007) classification, which determine the severity of the defect regarding to size, extension and location. This classification was performed in two moments by a single trained researcher (LBM) with an interval of 30 days between them (Kappa coefficient: 0.921). Any disagreements were reviewed and solved by further discussion with an expert researcher (VAPF). The volumetric evaluation of the orbital cavities (unaffected and reconstructed) was performed by two methods: image sectioning (IS) and computerized segmentation (CS).

Volumetric Evaluation by Image Sectioning

DICOM data of each patient was imported into the software OnDemand 3D 1.0.10.5385 (Cybermed, South Korea) and the volume reconstructed to generate two-dimensional images of the area of interest in a standardized way (bilateral orbits). The image display contrast was standardized (W=3086 and L=667). The volumes were reoriented to standardize the head position of all patients. Continuous images with 1-mm thickness were obtained from the coronal slices and exported as TIFF image (96 dpi resolution). The first coronal section was the one in which the bone structure of the orbital rim can be observed as a whole (Figure 1A). The posterior limit was defined by the disappearance of any structure of the orbital cone. For calibration, each image had a 2-cm ruler spaced every 1-mm.

The TIFF images of each patient were imported to Image J 1.51 (National Institutes of Health, United States) and a single calibrated researcher (LBM) traced the orbital limits manually with the help of the graphic table Wacom Intuos CTL-480 (Wacom, United States). Based on Cavalieri's principle, the sum of areas of the images results in a volume. For evaluation of intraobserver reproducibility 30% of the sample was assessed in duplicate (ICC: 0.846).

Volumetric Evaluation by Computed Segmentation

The DICOM data was imported to Osirix 5.6.32 (Pixmeo, Switzerland). Initially, the head position was standardized using MPR function similarly to the IS method. Then, the Region of Interest (ROI) was limited on the coronal slices, every 4 mm. Again, the first coronal section was the one in which the all bone structure was observed, and the posterior limit the disappearance of any structure of the orbit. Therefore, the orbital volume was generated automatically and recorded (Figure 1B). After this step, each coronal slice was reviewed and any ROI distortion was manually corrected (Figure 1C), and the orbital volume was calculated again. Thirty percent of the sample was analyzed in duplicate for evaluation of intraobserver reproducibility evaluation (ICC: 0.913).

Anteroposterior eyeball position evaluation

DICOM data previous imported into Osirix software were selected in the axial section in the middle of the orbit. To determine the anteroposterior position of the eyeball, the distance from a perpendicular line to that formed laterally between the zygomatic lateral areas in the central section of the eyeball, in which the optic nerve was visualized were measured[20] (Figure 1D). For evaluation of intraobserver reproducibility, 30% of the sample was assessed in duplicate (ICC: 0.966)

Sample Size

Sample size calculation was based on literature data stating that differences of up to 8% in volume are thought to be anatomical[21]. Consequently, higher than 8%

changes in volume are sufficient to determine a significant difference between the unaffected and reconstructed orbits. Therefore, we had assumed a standard deviation around 10%, as previously suggested in literature[22], and 60 CT scans was sufficed to provide a sample with 80% statistical power in a "non-inferiority" model[23].

Data evaluation and Statistical analysis

The orbital volume was measured until the end of the titanium mesh and the complete orbit. Then the volume between orbits and anteroposterior eyeball position were compared. Differences up to 8% in volume[21, 24] and up to 2 mm in eyeball position[20] were considered normal. Statistical analysis was performed to compare unaffected and reconstructed orbit, IS and CS methods, in the software IBM SPSS Statistics 18.0 (IBM, United States). When data distribution was normal, a paired t-test was performed; when the data had non-normal distribution, Wilcoxon test was performed. To correlate volumetric data, defect classification, and anteroposterior eyeball position Pearson correlation coefficient were obtained. To compare IS and CS methods a t-test was applied. In all cases, a 95% confidence interval was considered.

Results

This study included 60 patients with unilateral orbital fractures treated by titanium mesh. Of them, 47 were male and 13 female (ratio 3.6:1). The mean age was 46.27 (SD: 20.52 years), from 16 to 89 years. Regarding to defect classification, 83.3% involved only one orbital wall (n=50) and 16.7% two orbital walls (n=10). The most affected region was the orbital floor (70.0%), followed by the combination of orbital floor and medial wall (16.7%), and isolated medial wall (13.3%). About defect severity[7], 85% of the cases showed Class II and Class III defects, most of them in isolated orbital floor fractures. Class V defects were not found (Table 1).

In IS method, there was no statistical differences between unaffected and reconstructed orbits, in complete volume (p=0.852) and until the end of the mesh (p=0.320) (Table 2, Figure 2). Therefore, this result demonstrates the treatment using titanium mesh reestablished the orbital volume. The changes between orbital volumes varied from -7.15% to 10.46% (mean: -0.15%; SD: 3.96%), only two cases did not respect the anatomical differences of 8%. The comparison between volume changes of complete orbit and of until the end of the mesh was not statically significant (p=0.070).

Is CS method, there were three evaluated orbital volumes: pre-correction, post manual correction, and until the end of the mesh. There were no statistical differences between unaffected and reconstructed orbits in pre-correction (p=0.987), post manual correction (p=0.902), and until the end of the mesh (p=0.953) (Table 2, Figure 1). Thus, the treatment reestablished the orbital volume. Volume changes between orbits varied from -6.32% to 9.69% (mean: -0.01%; SD: 3.88%). Again, the same two cases did not respect the anatomical differences of 8%. The comparison between volume changes of complete orbit and of until the end of the mesh was not statically significant (p=0.200).

The anteroposterior eyeball position showed all measurements within anatomical differences of 2 mm. The measurements varied from -0.9 mm to 1.8 mm (mean: 0.35 mm; SD: 0.59). Pearson's correlation test between defect severity, orbital volume changes, and anteroposterior eyeball position were not statistically significant (Table 3). Also, the comparison between IS and CS was not statistically significant, unaffected orbit (p=0,630) and reconstructed orbit (p=0.641).

Discussion

Orbital fractures are common in facial trauma and results in important clinical changes regarding to aesthetics and function[3, 25]. Among the complications, highlight enophthalmos – due to increased orbital volume or tissue atrophy – and diplopia – due to inadequate eyeball position, increased orbital volume or muscle entrapment[7, 15, 26]. Thus, the main complications of orbital fractures are related with orbital volume and eyeball position.

Orbital defect extension and severity has an important role correlated with volumetric changes and clinical symptoms[7, 27]. The number of involved walls, region and size of defect determine the severity of the fracture. In this study, most of fractures showed Class II and Class III defects, 41.6% and 43.3% respectively, and were localized in orbital floor and/or medial wall. Those defects are commonly found in high energy trauma indirectly to the eyeball[7, 28].

Due to adopted inclusion and exclusion criteria only orbital floor and/or medial wall fractures were analyzed. From the sample, 83.4% of the cases presented one wall fracture (70.1% orbital floor and 13.3% medial wall), and 16.6% the combination of orbital floor and medial wall fractures. Oh et al.[13] examined a similar sample composed by orbital floor and/or medial wall fractures. The authors analyzed the orbital volume at two moments, pre- and postoperatively, and observed that combined fractures had the major volumetric enlargement preoperatively. After the surgical treatment, all fractures showed a decreased volume, however just the isolated medial wall fractures had differences between orbits minor to 8%. Volumetric studies in health patients report that the orbital volumes are not symmetric, and the differences up to 8% are normal without clinical changes[21, 24]. Thus, we considered 8% differences a reasonable volumetric outcome after orbital reconstruction. In our sample, although combine fractures showed major volumetric differences, just two cases showed volumetric enlargement higher than 8%, one case of isolated medial wall fracture and other of isolated orbital floor fracture. Those cases did not respect the orbital anatomy and contour.

The unaffected orbital cavity can be defined as control parameter due to non-significant differences between the orbital volumes. Eventual differences may occur due to anatomical changes and to errors during image acquisition[10, 13, 22]. Also, in non-syndromic patients, differences up to 8% are considered within anatomical parameters[21, 24].

In previous studies, the preoperative orbital volume evaluation was applied to establish parameters to indicate the need of surgical treatment[27, 29, 30]. Being verified that the surgical treatment is dependent of the enlargement of orbital volume, the damage to bone structures, presence of enophthalmos, and soft tissue displacement[29]. Therefore, the treatment aim to restore three-dimensionally the anatomy in order to obtain the orbital volume prior to trauma[25, 26].

In this study, the postoperative orbital volume was evaluated by two methods, CS and IS. The comparison between methods was not statistically significant, therefore both methods are feasible to calculate the orbital volume with similar results. Besides, in both methods, there was no statistical difference between unaffected and reconstructed orbital volumes – complete orbit and until the end of the mesh – which demonstrate that the treatment using titanium mesh reestablished the orbital volume.

Regardless of the method of volumetric evaluation, the region of interest was delimited in coronal slices, being the anterior limit the first slice with presence of all orbital walls, and the posterior limit the disappearance of any structure of the bone orbit. Scolozzi et al.[2], applied similar methodology and analyzed 12 orbital fractures after treatment by CS method. The authors found similar results, and none of the reconstructions presented volumetric differences major than 8%.

The determination of the anterior limit of the orbit for volumetric evaluation is discussed in the literature. The point of discussion is how to accurately define the anterior border of the bone orbit[22, 26, 31]. Kwon et al.[22] verified orbital volume using three methods for determination of the anterior limit of the orbit. They concluded that coronal slices may underestimate the total orbital volume, and the evaluation using axial slices is the most reliable method. However, our study aimed to verify if the reconstruction using standard titanium mesh reestablishes the orbital volume, when compared to the unaffected orbit. Thus, we considered the analysis using coronal slices adequate, and in case of underestimation of the total volume, the volumetric differences between orbits would be exacerbated. In the analyzed sample, only two cases showed volumetric differences higher than 8%.

Moreover, it is important to highlight the aim of the volumetric analysis and the influence of the total volume of the orbit. In reconstructed orbits, the volume of non-fracture areas may compensate any contour errors. Therefore, we also calculated the orbital volume just in the reconstructed areas, limited by the end of the titanium mesh, and the same slices of the contralateral orbit. Again, in both methods of evaluation there were no statistically significant differences between the orbits.

Enophthalmos is closely related to the increased orbital volume. Several studies confirm this relationship, and report that each increased 1 cm3 result in in 0.89 mm enophthalmos[4, 10, 15, 26, 30, 32-34]. As previous described, in non-syndromic patients enophthalmos up to 2 mm are considered within anatomical parameters[25, 26, 33]. In this study, all patients presented the tomographic anteroposterior eyeball position within anatomical parameters, and this fact usually is related with the correct volumetric reestablishment obtained after reconstruction. However, no statistical correlation was observed between eye position and volumetric difference between the orbits. As hypothesis, we discuss the efficiency of the tomographic evaluation of the eyeball position, and we recommend further studies to compare with a clinical evaluation by Hertel exophthalmometer.

Another factor that influences the eyeball position is orbital fat atrophy[35]. Although Schuknecht et al.[36] described that orbital fat atrophy is an insignificant factor to the presence of enophthalmos, recent clinical study[35] demonstrate that adequate orbital volume and anatomic contour are essential, however they do not predict the clinical outcome. Moreover, Matsunaga et al.[37] analyzed the preoperative inferior rectus muscle swelling in orbital floor fractures. The authors found a positive correlation between diplopia, eyeball movement restriction and the muscle swelling. Therefore, the role of orbital fat atrophy and extraocular muscle swelling still has to be explored.

Our study was able to determine that both methods, IS and CS, are feasible to calculate the orbital volume. During the study, we realized that CS method was easier and faster to be performed, however it should be confirmed by further studies. Moreover, the included sample size allowed the comparison between unaffected and reconstructed orbits, regarding to volume and anteroposterior eyeball position. However, some limitations are present as the absence of pre- and postoperative clinical data and the volumetric analysis of extraocular muscles. Future studies should evaluate those features.

With the applied methodology, we conclude that the treatment with standard titanium mesh reestablished orbital volume and anteroposterior eyeball positon in orbital fractures. This conclusion is especially spread for Class II and III defects, which were the most found type of defect.

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Table 1 – Defect severity and involved walls.

Orbital wall	Classification				Total
	I	II	III	IV	
Orbital floor	4	16	20	2	42
Orbital floor and medial wall	-	1	6	3	10
Medial wall	-	8	-	-	8
Total	4	25	26	5	60

Table 2 – Mean, standard deviation, in cm^3, and statistical analysis of orbital volumes evaluated by IS and CS methods.

Region	Orbit	IS[c]	CS[c]
		Mean ± SD	Mean ± SD
End of the mesh	Unaffected	13.95 ± 2.71	13.55 ± 2.35
	Reconstruced	13.91 ± 2.83	13.62 ± 2.47
	p-value[a]	0.953	0.902
Complete orbit	Unaffected	16.36 ± 2.12	16.53 ± 1.77
	Reconstruced	16.34 ± 2.26	16.53 ± 1.89
	p-value[b]	0.320	0.852
Complete orbit pre-correction	Unaffected	-	16.40 ± 1.79
	Reconstructed	-	16.69 ± 1.98
	p-value[b]	-	0.987

[a] Wilcoxon test

[b] paired t-test

[c] Comparison between methods using t-test (p>0,05)

Table 3 – Pearson's correlation test between defect severity, orbital volume changes (IS and CS), and anteroposterior eyeball position.

	Defect severity	Orbital volume change (IS)	Orbital volume change (CS)	Eyeball position
Defect severity	1	0,076	0,105	0,003
p-value	-	0,566	0,425	0,980
Orbital volume change (IS)		1	-	-0,004
p-value		-	-	0,974
Orbital volume change (CS)			1	-0,052
p-value			-	0,691
Eyeball position				1
p-value				-

Legend of figures

Figure 1. A. Determination of the region of interest in IS method. **B.** CS method automatic generated. **C.** CS method after manual correction. **D.** Anteroposterior eyeball position.

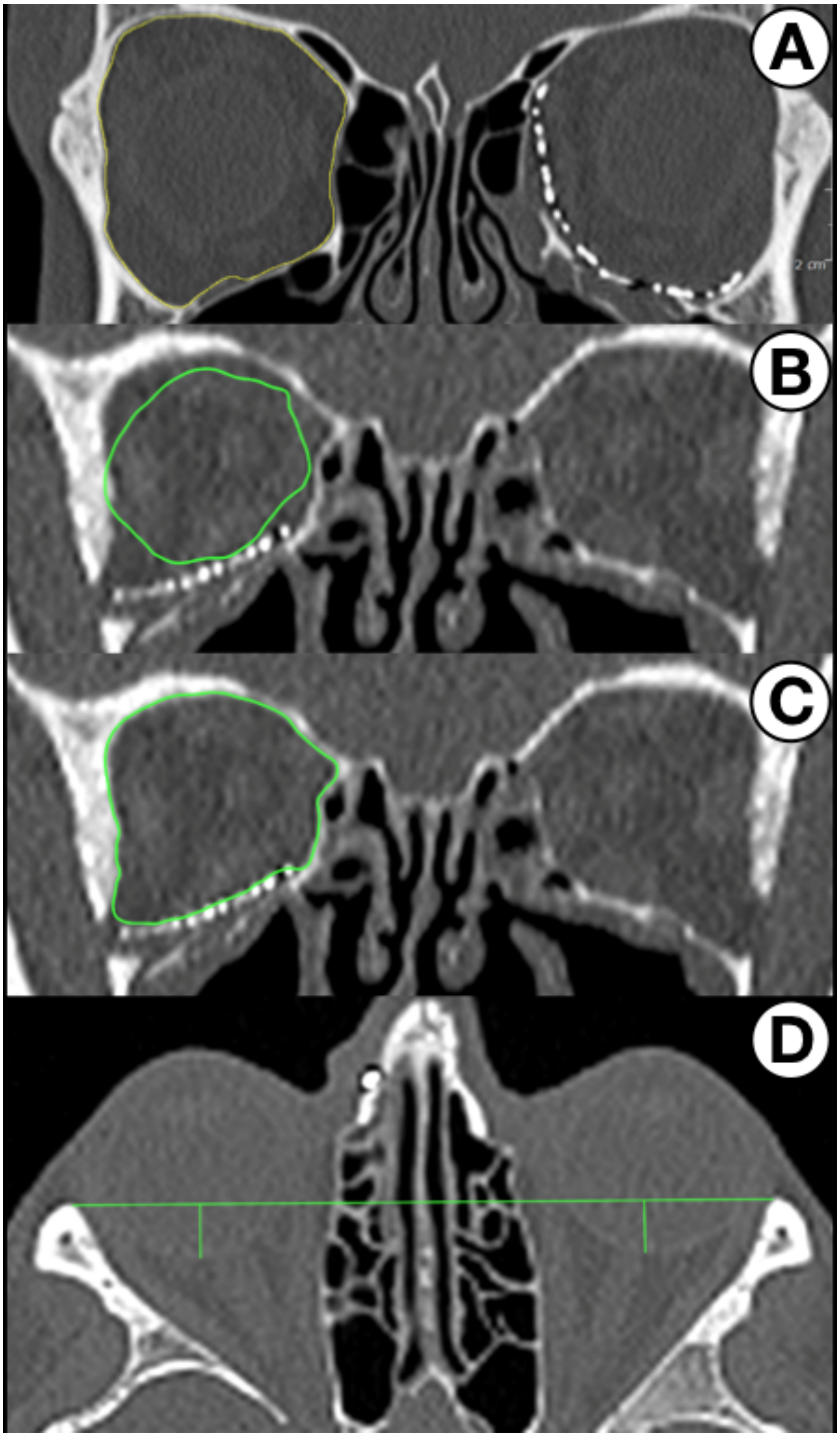
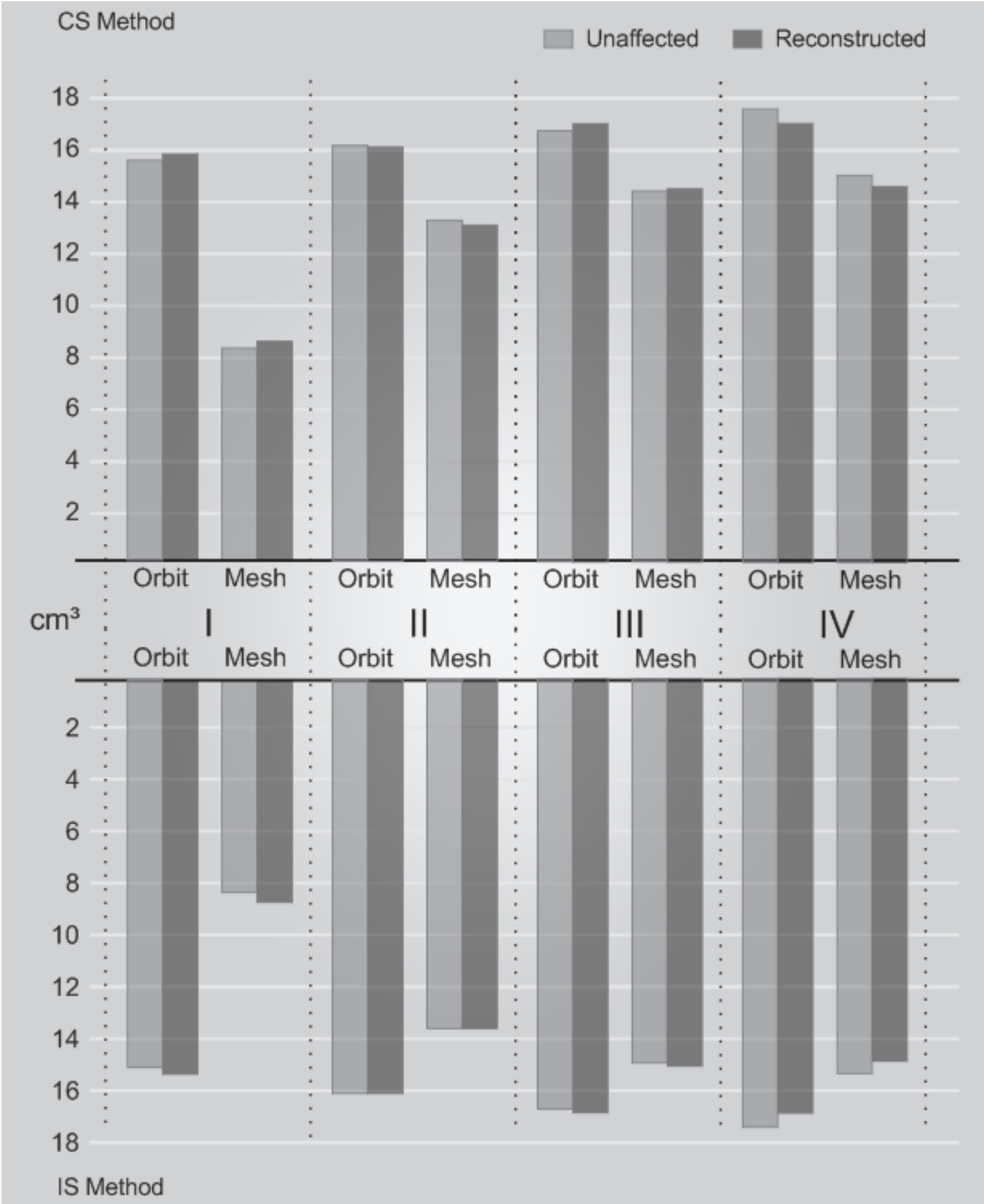


Figure 2. Mean of reconstructed and unaffected orbital volumes, complete orbit and at the end of the mesh, regarding to defect severity, CS and IS methods.



4 ARTIGO 2 – Dynamic three-dimensional finite element analysis of orbital trauma*

Dynamic Three-Dimensional Finite Element Analysis of Orbital Trauma

Short title: 3D FEA of Orbital Trauma

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Abstract

This study does a dynamic finite element (FE) analysis of orbital trauma mechanisms – buckling and hydraulic theories. A complete digital model of the orbital cavity – including eyeball, fat tissue, extraocular muscles and bone orbit - was created from MRI and CT data from a real patient. An impactor hit the FE model in two scenarios: direct to the eyeball, and in infraorbital rim. The first principal stress was calculated to determine stress distribution. The complete FE model presented more than 900,000 elements and time of simulation was 4.8ms and 0.6ms, to hydraulic and buckling mechanisms, respectively. The stress distribution in hydraulic mechanism affected mainly the medial wall with high stress area of 99.08 mm^2, while the buckling mechanism presented a high stress area of 378.70 mm^2 in the orbital floor. The presence of soft tissue absorbed energy, especially in the hydraulic mechanism. In conclusion, the applied method of segmentation allowed the built of a complete orbital model. Both mechanisms presented results similar to the classic experiments. However, the soft tissue in the hydraulic mechanism absorbed the impact, demonstrating its role in the orbital pathophysiology.

Key-words: Orbit; Orbital fractures; Finite Element Analysis.

Introduction

Orbital fractures represent more than 40% of midface fractures[1, 2]. Their high prevalence is related to anatomical characteristics, such as the thin orbital walls, being mostly affected the orbital floor and medial wall[1, 3]. In 1957, Smith and Regan[4] first reported an orbital wall fracture. They described a complete dislocation of the orbital wall into the maxillary sinus without fracture of the infraorbital rim, a blow-out fracture[4].

Essentially, there are two theories that explain the pathophysiology of blow-out fractures – buckling and hydraulic mechanisms[5-7]. The buckling mechanism occurs by a direct impact over the infraorbital rim, the stress is transmitted to the orbital floor causing the fracture. The hydraulic mechanism is observed when a direct impact to the eyeball occurs. In this case, the internal pressure of the orbit abrupt increases and the stress is transmitted to the orbital walls[5-7].

Although both mechanisms are historically established, several studies were performed to achieve a better comprehension about the stress distribution features and fractures patterns[5-10]. Previous cadaveric studies[6, 10] described that the hydraulic mechanism needs a higher stress force to cause fracture when compared to the buckling mechanism. Also, the latter resulted in orbital floor fractures without soft tissue herniation, while the hydraulic mechanism caused medial wall fractures with soft tissue herniation into the paranasal sinuses[9]. Presently, the finite element (FE) method is applied to simulate facial trauma and analyze different scenarios[5, 7, 8, 11-14]. However, none of the published studies performed a tridimensional FE analysis on a complete orbital model containing all structures, including the eyeball, fat tissue, extraocular muscle and bone orbit.

The aim of this study was to build a complete digital model of the orbital cavity based in the real image exam from a patient and perform a dynamic FE analysis of the orbital trauma mechanisms.

Materials and Method

A finite element model of the orbital cavity was built from CT (0.5mm-thick slices) and MRI scans (1mm-thick slices) from a healthy patient. The DICOM (Digital Image and Communication in Medicine) data were imported to the software *Materialise Mimics 19.0* (Materialise, Leuven, Belgium) for manual segmentation of the orbital structures. The bone object was built from the CT data, and the orbital tissues (extraocular muscles, eyeball and fat tissue) were obtained from the MRI data.

The region of interest was defined as the left orbit part of the skull. The orbital part was cut out at the midline, 3 cm above the superior orbital rim, 4 cm below the inferior orbital rim and 1.5 cm behind the orbital apex. In order to obtain a realistic FE model from DICOM data the segmentation process followed specific steps. Firstly, an automatic segmentation based on Hounsfield value thresholds was done to obtain an initial model of the bone orbit. This model failed to represent thin cortical bone, such as the orbital floor and the medial wall. Therefore, each slice was manually edited in axial, coronal and sagittal views. Based on anatomical references and difference between grey values, a trained research (LBM) applied a one pixel brush (0.3 mm width) to fill the gaps and achieve correct anatomic contour and thickness. The extraocular muscles and the eyeball were also created from automatic segmentation and manual correction. However, the orbital fat tissue should fill all spaces between the bone orbit, muscles and eyeball, thus Boolean operations were applied to obtain the fat tissue (Figure 1).

After manual segmentation, all rough objects were imported to the software *Materalise 3-matic* (Materalise, Leuven, Belgium) for smoothing, refinement and diagnosis. In this step, all bad edges, holes, overlapping and intersecting triangles were corrected. Also, all objects were placed together to define the contact areas (Figure 1), and were exported as STL files.

All STL objects were imported to *ANSYS 18.1 software* (ANSYS Inc., Canonsburg, United States) to create the FE mesh and perform dynamic simulations. A finite element volume mesh with tetrahedral shaped 10-node elements was created for each structure. The complete FE model had 928,846 elements. A virtual brass weight (density: 8.4g/cm3; Young's modulus: 100,000 MPa; Poisson's ratio: 0.37) was modelled to simulate one single impact in two simulations representing respectively the hydraulic and buckling mechanisms[6, 12]. Each structure was defined with a specific material property according to previous studies – bone orbit[7, 8, 14, 15], extraocular muscles[16], orbital fat tissue[16], and eyeball[16]. We considered the eyeball filled with a liquid, therefore the Bulk modulus of water (2,200 MPa) was applied (Table 1).

A local coordinate system along the axis of the impactor was created and a velocity of 6 m/s[5, 12] was applied. To obtain the force distribution through the eyeball, the impactor was rotated 20^o laterally, aligned to the orbital apex and placed parallel to Frankfurt plane[5]. In the hydraulic mechanism, the impactor hit the eyeball directly in the center, whereas in the buckling mechanism the impactor hit the center of the infraorbital rim (Figure 2).

The bone structure was fixed in all degrees of freedom in the superior, posterior and medial edges. The contact areas between each object were defined as bounded for bone orbit to orbital fat, orbital fat to extraocular muscles, muscles to eyeball, and orbital fat to eyeball, as well as frictional – 0.4 coefficient factor[14] – for impactor to bone orbit and impactor to eyeball. The tridimensional stress over the orbital walls was analyzed by the 1st Principal Stress. In each simulation, the most affected areas were measured for comparison.

Results

The applied methodology for CT and MRI segmentation allowed the design of a high detailed FE model of the orbital cavity. The FE mesh presented 928,846 elements. In each simulation, the 1st Principal Stress, peak of impact and impact time interval were calculated.

The hydraulic mechanism simulation lasted 4.8ms, and a time-step of 66 μs was applied for evaluation. Total impact energy of 7750 N was verified with a peak of impact at 1.8ms. The results of the dynamic analysis are reported in Figures 3 and 4. Figure 3 shows the tridimensional distribution of the 1st Principal Stress, being the most affected region the medial wall. Stress higher than 60N was verified in an area of 99.08 mm2 on the medial wall. Figure 4 shows the historic stress distribution over the orbital walls and regions. It is observed that the higher stress was concentrated at the middle third of the medial wall.

The buckling mechanism simulation was shorter and lasted 0.6ms. A time-step of 8 μs was used for evaluation and total impact energy of 6700 N was observed, with a peak of impact at 0.27ms. Figures 5 and 6 show the results of dynamic analysis. Figure 5 shows the tridimensional stress distribution over the orbital walls, specially to the orbital floor. Figure 6 shows the historic distribution of stress over the orbital walls and regions. The higher stress was concentrated at the medium and posterior third of the orbital floor and the medial wall was almost not affected. Stress higher than 60N was verified in a 378.70 mm2 area of the orbital floor.

The time-step and time of simulation between the mechanisms were considerably different. In the hydraulic mechanism, the eyeball, fat tissue and extraocular muscles suffered deformation, whereas in the buckling mechanism the bone object was directly hit. Video 1 shows both mechanisms and 1st Principal Stress distribution during the whole simulation time.

Discussion

Orbital fractures are highly prevalent[1] and their biomechanics is a constant focus of discussion[5-10, 16]. Previously, the investigation of trauma biomechanics was not feasible, due ethical and reliability issues. Human cadavers were often used[6, 10], however some post-mortem changes were present and did not represent a typical patient with facial injury[12]. Therefore, the FE is a valid method to analyze trauma biomechanics. The current studies that evaluate orbital fractures applying FE analysis show limitations as the use of CAD models[7, 8, 17] or lack of structures[5] – e.g. absence of fat tissue and extraocular muscles. In our study, all orbital structures – bone, eyeball, fat tissue and extraocular muscles - were obtained from CT and MRI scans from a real patient.

The building process to obtain a digital model of the orbital cavity should follow specific steps as the automatic thresholding, manual slicing and proper refinement. The bone structure was obtained from 0.5-mm CT scanning. However, the automatic segmentation was not able to include the thinner cortical bone, mainly in the medial wall and orbital floor. This was also observed by Huempfner-Hierl et al[13] and Schaller et al[14] and a manual slicing in coronal, axial and sagittal planes was performed to fill those undefined areas. As the CT scan is the best image exam to evaluate bone structures, MRI allows the optimal evaluation of orbital soft tissues[5, 18, 19]. Therefore, eyeball, fat tissue and extraocular muscles were obtained from MRI data, as described by Schutte et al[19]. The association of CT and MRI scans allowed to create a complete digital model of the orbital cavity.

Two different FE analysis of orbital fracture pathophysiology are present in the literature: static[7, 8, 17] and dynamic[5]. Our study evaluated orbital wall stress after a dynamic impact, which is more realistic and has advantages in relation to the static method[5]. It was possible to analyze the stress over the bone structure from the beginning of impact until the end of simulation. Also, the tissue's viscoelastic response allowed a more realistic scenario about the impact[5], particularly in the hydraulic mechanism.

In our study, the most affected regions varied according to the type of mechanism. The buckling mechanism distributed stress mainly in the orbital floor – anterior and medium thirds. This find was similar to previous FE studies[5, 7, 8] and it is explained by the theory that a direct impact to the infraorbital rim causes a transient deformation of the rim and the force is distributed to the orbital floor[10, 20]. In Video 1 it is possible to observe the transient deformation of the infraorbital rim. Moreover, this result is similar to the cadaveric study from Waterhouse et al[6], where the majority of fractures occurred in the anterior region of the orbital floor, without involvement of the medial wall.

In the hydraulic mechanism, the resultant stress affected mainly the medial wall, especially the medium third, and the stress area was minor when compared to the buckling mechanism. This mechanism theory proposes that a direct impact to the eyeball increases the internal hydraulic pressure and it is transmitted to the thin orbital walls[10, 21]. These results are similar to those described by Nagasao et al[7], where the hydraulic pressure resulted in a small affected area located at the medial wall. However, Schaller et al[5] found a different scenario with a major stress distribution in the junction between the orbital floor and medial wall. This difference may be explained due to the applied methodology. Schaller et al[5] created an artificial eyeball with contact to all orbital walls, whereas we created the eyeball from MRI scan and it was involved by the orbital fat.

The resultant stress values over the orbital walls in the hydraulic mechanism were significant minor when compared to those found in previous studies[5, 7]. As already described, our FE model included orbital fat and extraocular muscles. Therefore, we believe that the impact was absorbed by the soft tissues and consequently the transmitted stress was minor. Moreover, previous FE models presented some uncertain aspects, such as the overrated contact between eyeball and orbital walls[5] and the direct static force applied to the orbital walls[7].

Two main limitations are present in our FE model. Bone failure was not incorporated and a uniform Young's modulus and Poisson ratio were applied to the bone structure. Failure would be important to create an optimal model, where the failing elements (fracture) are erased and the simulation recalculated according to new boundary conditions[13], whereas an specific Young's modulus for each voxel, according to the CT Hounsfield data, would be helpful to increase the differences between the orbital walls[14]. Those features should be applied in future studies.

In conclusion, the applied methodology allowed construction of a complete digital orbital model. The presence of fat tissue and extraocular muscles has an important role on impact absorption and stress transmission to the orbital walls. Both mechanisms of injury were validated and present similar results in the literature. The buckling mechanism mainly affects a large area of the orbital floor, whereas the hydraulic mechanism results in a smaller area of stress in the medial wall.

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Table 1 – FE mesh features and material properties of each orbital structure.

Structure	Elements (n)	Nodes (n)	Young's Modulus (MPa)	Poisson's ratio	Density (g/cm3)
Bone	363,169	76,282	13.5	0.32	1.591
Extraocular muscles	149,113	30,305	11.0	0.4	1.06
Orbital fat tissue	339,883	66,341	0.5	0.49	0.999
Eyeball	65,389	14,698	2.2[a]	0,49	0.999
Impactor	11,292	2,566	100,000	0.37	8.4
Total	928,846	190,192	-	-	-

[a] Bulk modulus

Legend of figures

Figure 1. A. Manual segmentation of orbital structures. **B.** Orbital fat obtained after Boolean subtraction. **C and D.** Refinement and definition of contact areas.

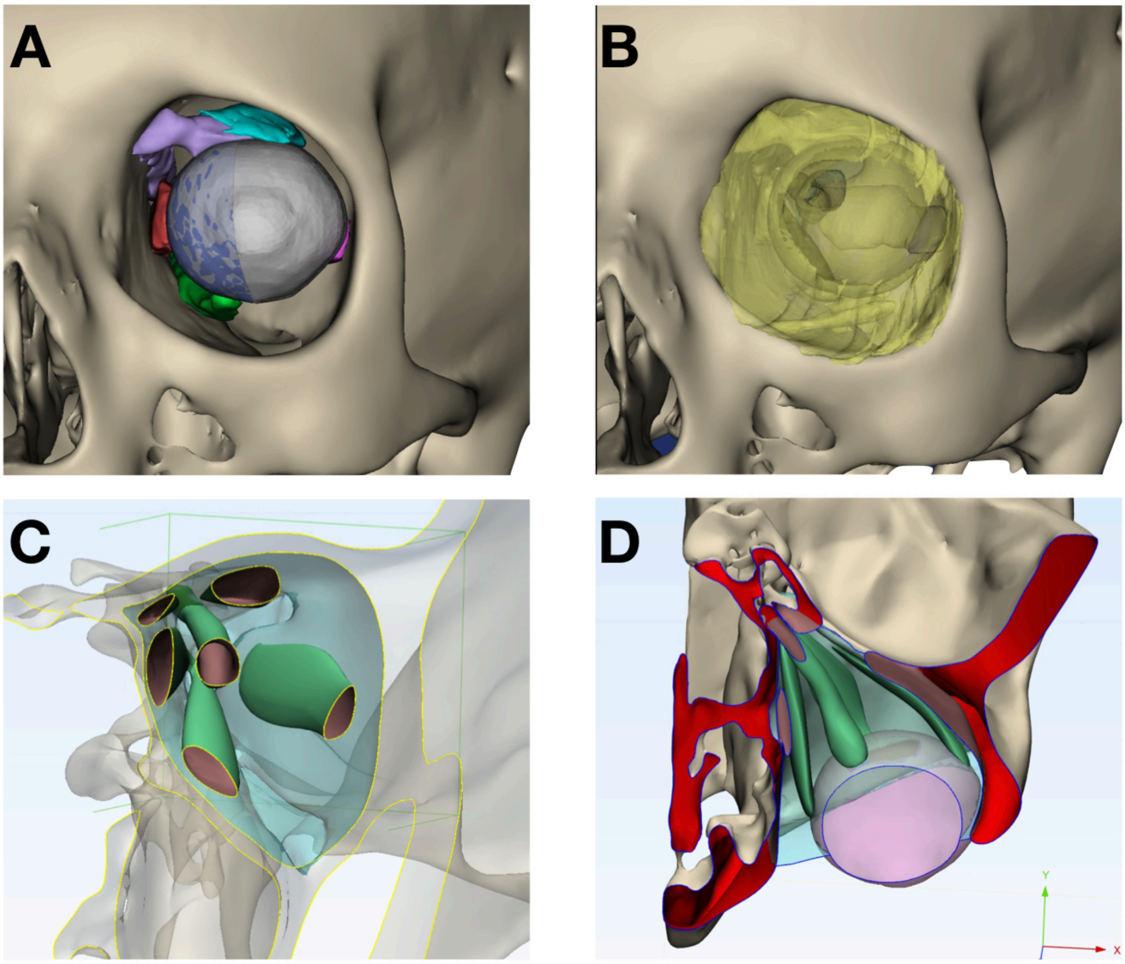


Figure 2. Hydraulic (A) and Buckling (B) mechanisms.

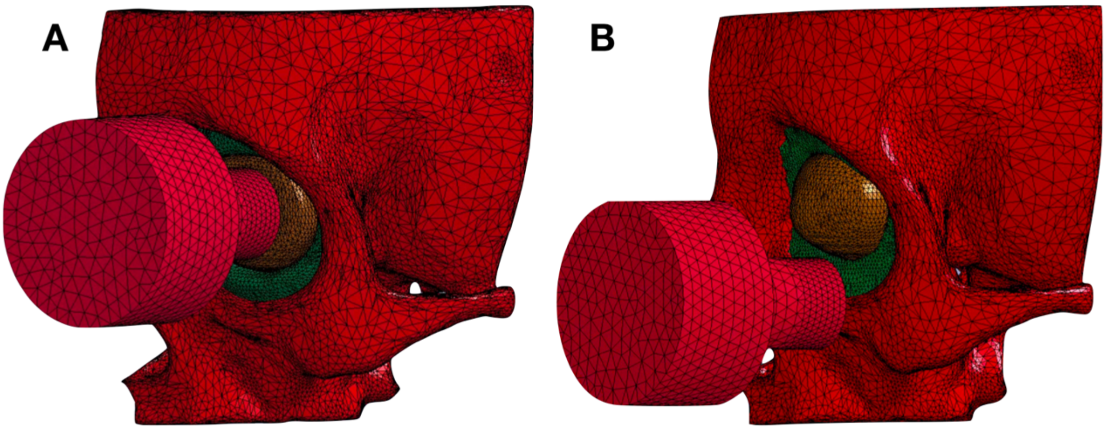


Figure 3. Distribution of 1st Principal Stress over orbital walls in hydraulic mechanism.

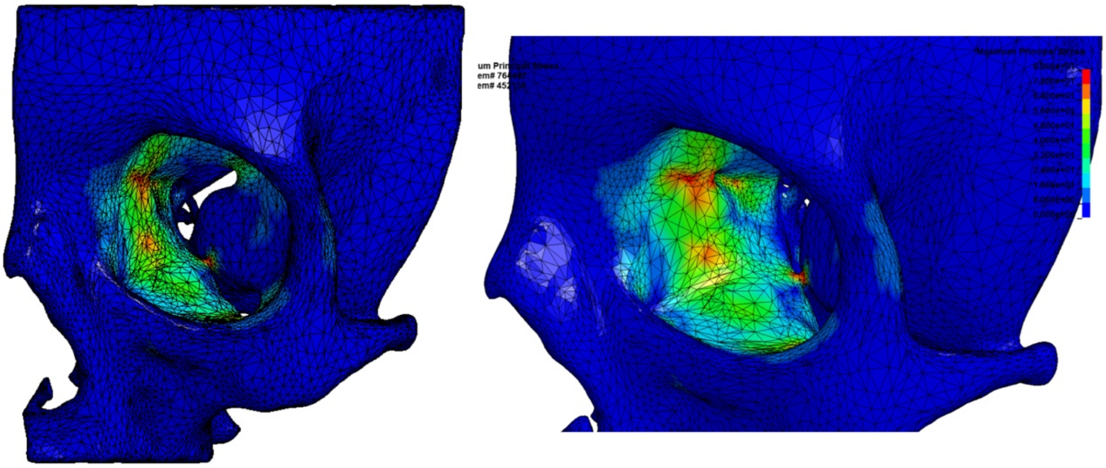


Figure 4. Distribution of 1st Principal Stress over orbital walls and regions, according to time step, in hydraulic mechanism.

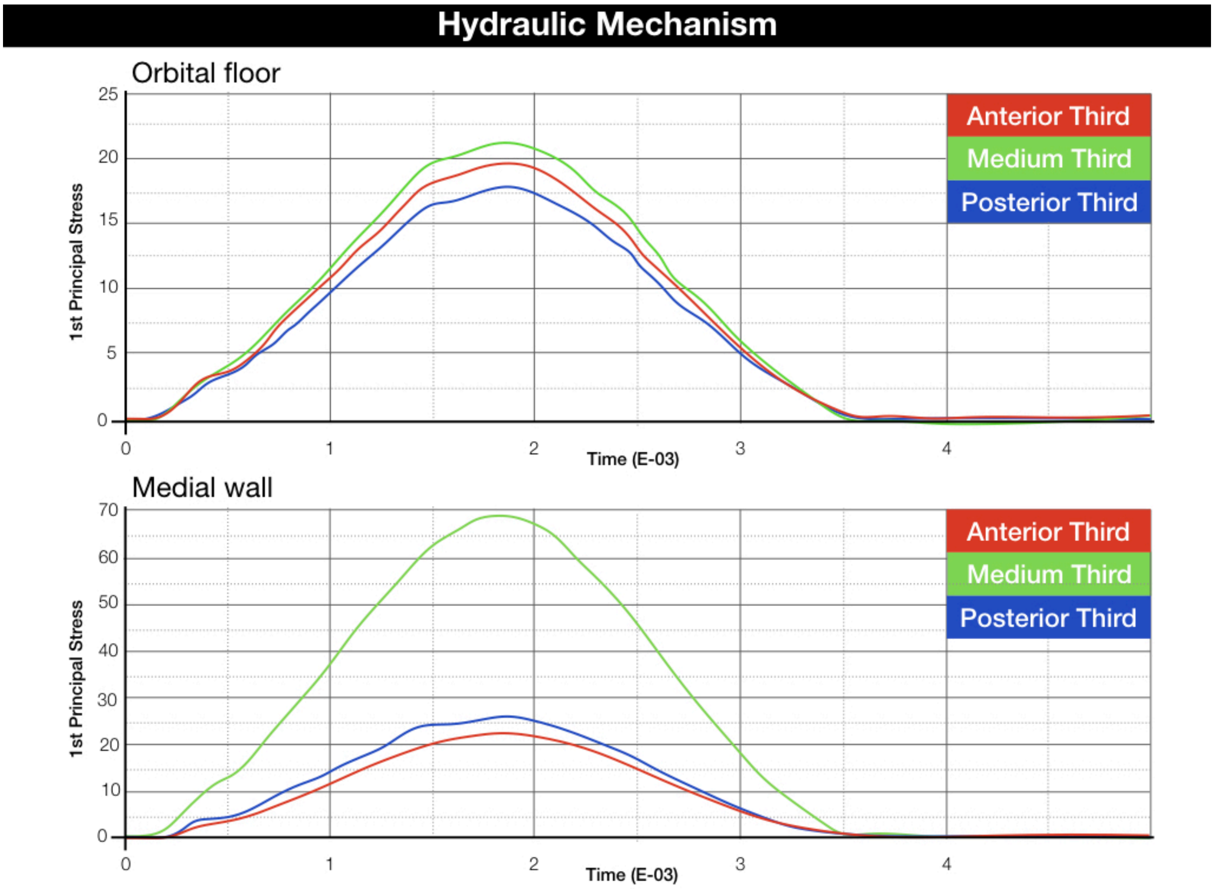


Figure 5. Distribution of 1st Principal Stress over orbital walls in buckling mechanism.

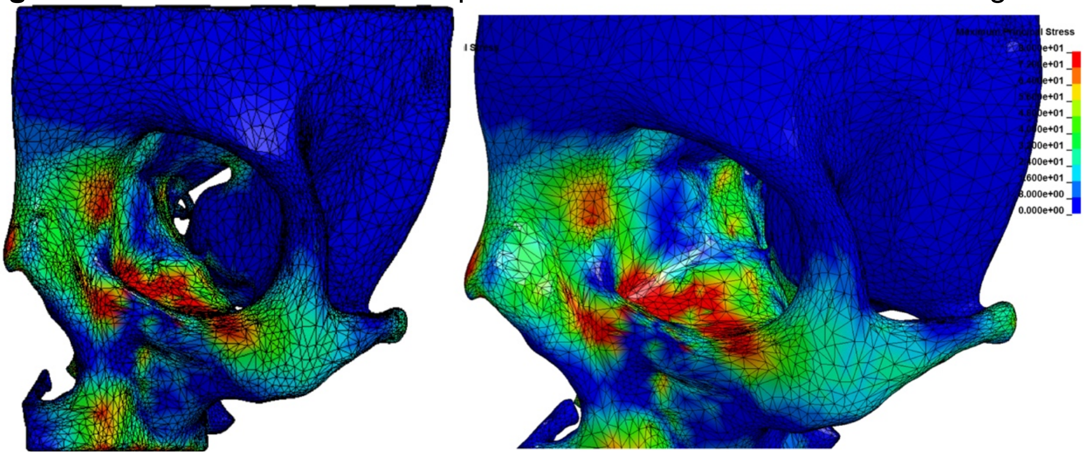
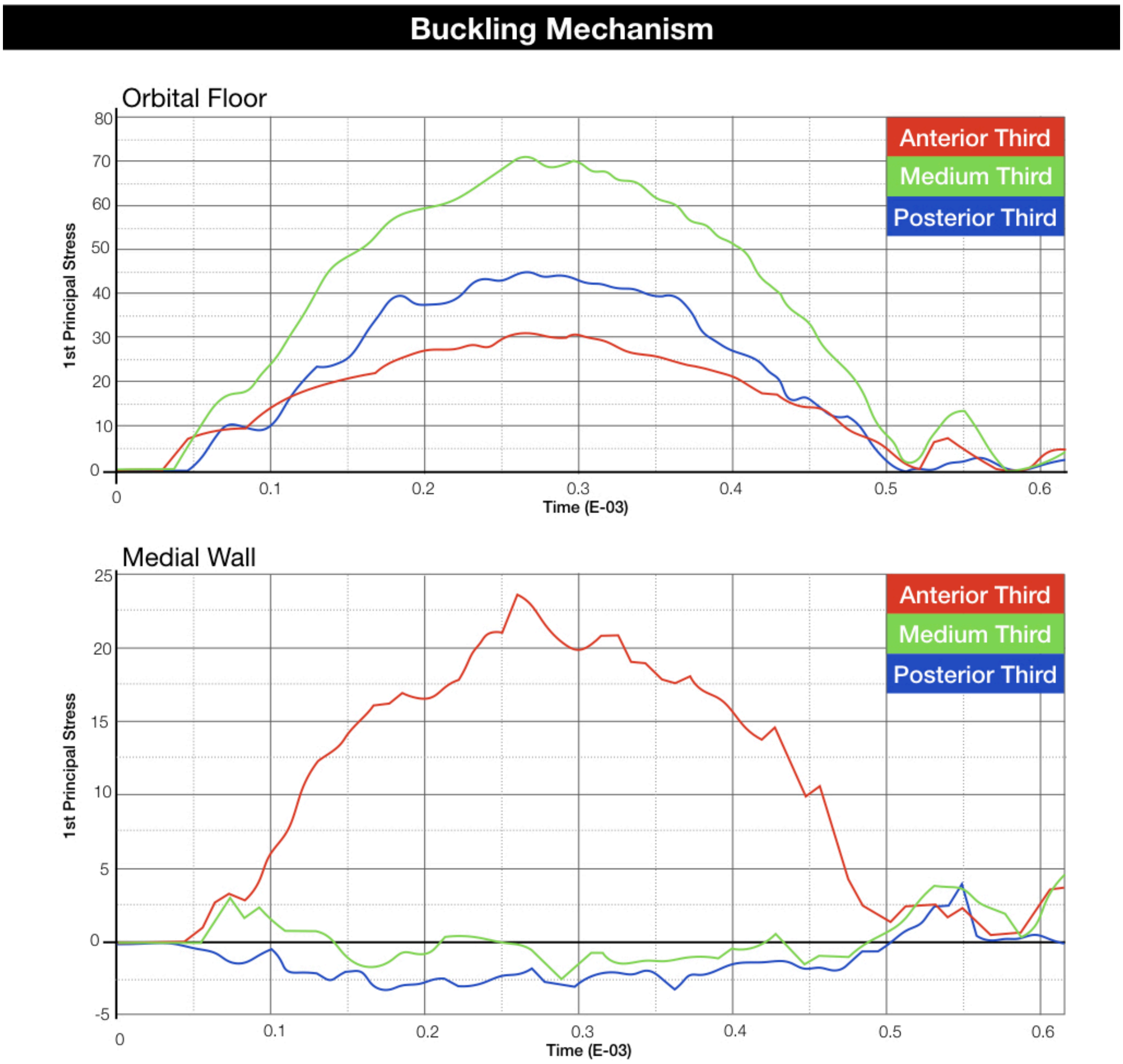


Figure 6. Distribution of 1st Principal Stress over orbital walls and regions, according to time step, in buckling mechanism.



5 ARTIGO 3 – Reconstruction of orbital floor defects assisted by transantral endoscopy*

Reconstruction of orbital floor defects assisted by transantral endoscopy

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Abstract

Purpose: The goal of orbital reconstruction is to restore anatomy, volume and function. In extensive orbital floor defects, the visualization of the posterior area is limited through inferior eyelid incisions. The use of endoscope may improve the treatment however it is a high sensitive technique. The aim of this case series is to describe the combination of inferior eyelid incision with transantral endoscopy for treatment of extensive orbital floor defects. *Methods:* Three patients were submitted to orbital reconstruction and the postoperative CT scans were evaluated to analyze the orbital volume and anteroposterior globe position. Surgical treatment were performed using subciliary inferior palpebral approach to explore the orbital floor and placement of the titanium mesh and an intraoral antrostomy for endoscopy to magnification of the surgical field and adaptation of the mesh. *Results:* Postoperative CT scan analysis shows that all treatments restored orbital volume and globe position without compression or damage of the optical nerve. *Conclusion:* The use of endoscope allowed the precise visualization of the posterior region of the orbit and adaptation of the titanium mesh.

Key words: Blowout fracture. Endoscopic repair. Orbital floor. Tomography.

Introduction

Orbital fractures represent more than 40% of all midface fractures. The most prevalent regions are the orbital floor and medial wall [1]. The resulting bone defects may cause a prolapse of orbital content to paranasal sinuses and the entrapment of extraocular muscles [2]. When this occurs, diplopia, enophthalmos, dystopia and ocular movement restriction can be present and surgical treatment is recommended [1-4]. Traditionally, the treatment of orbital floor fractures is performed by inferior eyelid incisions [5]. However, in extensive bone defects the visualization of posterior orbit and the adaptation of implants can be difficult through those incisions [2,6].

The use of endoscope in orbital fractures allows a better evaluation and visualization of bone defects and treatment improvement [7]. Small fractures of medial wall and/or orbital floor can be treated only by transnasal or transantral endoscopy without skin incisions [2,8]. However, in extensive fractures the reconstruction only with endoscope is difficult and require a high sensitivity technique [8]. Alternatively, the combination of inferior eyelid incision and endoscopy are used to treat this kind of fracture [3]. Palpebral approaches provide an easy access for implants and the endoscopy allows the visualization of the posterior region [5,7]. The aim of this case series is to describe the reconstruction of extensive orbital floor defects using a combination of palpebral approach and transantral endoscopy and the advantage to use this combination.

Case series

Three patients with extensive orbital floor defects were selected to orbital reconstruction using titanium mesh. All patients were treated by inferior eyelid incision and intraoral antrostomy with transantral endoscopy. The patients were placed in reverse trendelemburg position to facilitate the use of endoscope. The subciliary approach was chosen allowing adequate exposure of the orbital walls. Simultaneously, through an intraoral incision, a bone window (2cm width x 1cm height) was performed in the anterior wall of maxillary sinus, observing a distance of 5mm from apex of the teeth and infraorbital foramen. A 30-degree endoscope was used to explore the maxillary sinus, to remove the sinus mucosa around the fracture and verify defect extension and orbital tissue prolapse (Figure 1). The titanium mesh was placed through palpebral approach. The implant adaptation and absence of entrapment of extraocular muscles were verified using transantral endoscopy (Figure 2).

A volumetric evaluation of postoperative CT scans was realized to compare reconstructed and healthy orbits. The DICOM files were imported into software OnDemand 3D 1.0.7.0295 (Cybermed, Seoul, Korea) to make tridimensional volumes and axial, coronal and sagittal slices. The volumes were reoriented to standardize the head position of all patients. Continuous images with 1-mm thickness were obtained from coronal slices. The initial image was the first slice that showed all orbital rim and the final image was the end of orbital cone. Based on Cavalieri's principle the sum of areas of the images results in a volume. Differences between orbits up to 8% are considered anatomical [9].

From the axial slice in center of the orbit, the anteroposterior position of the eyeball was evaluated. On this image was measured the distance from the posterior region of the central section of eyeball to a line formed between the zygomatic regions bilaterally [10]. Differences up to 2 mm are considered anatomically normal

[10]. Table 1 shows defects classification, orbital volumes and difference between the anteroposterior position of eyeballs.

Patient #1

A 28-year-old healthy woman suffered car accident 17 days before consult. Physical examination showed a lower eyelid scar, upper eyelid ptosis, enophthalmos, ocular movement restriction and diplopia in left eye. CT scan demonstrated left orbital floor fracture with extension to posterior region and involvement of inferior orbital fissure, size more than $2cm^2$, a category IV defect [11]. Using the described technique, a titanium mesh was placed to reconstruct the orbit. In the early postoperative period was verified excessive ocular scleral exposure due to scar retraction. The treatment was local physiotherapy. In a month follow-up, there was a resolution of clinical complaints. Volumetric analysis and the eyeball position are according to anatomical limits.

Patient #2

A 19-year-old healthy woman was attended in Emergency Hospital due to car accident. Physical examination showed diplopia and ocular movement restriction to up and down. In CT scan was observed a category III [11] defect of right orbital floor with involvement of inferior orbital fissure. The combination of inferior eyelid incision with transantral endoscopy allowed the signal and symptomatology resolution and restoration of orbital volume and anteroposterior eyeball position.

Patient #3

A 33-year-old man admitted in Intensive Care Unit due to car accident with multiple body fractures. Oral and maxillofacial evaluation was required due associated facial trauma. In physical exam, the patient was sedated and unresponsive. A facial asymmetry in left zygomatic region was observed. CT scan showed zygomatic fracture with extensive orbital defect in floor and medial wall – Category IV [11]. Surgical treatment was performed using the combination of approaches and a supraciliary approach to reduce the sphenozygomatic suture. Postoperative period was uneventful, however due to systemic injuries the patient died.

Discussion

Usually, orbital floor fractures are comminuted and these bone defects may extend to posterior area or medial wall according to trauma intensity [3,12]. Inadequate treatment may lead to sequelae such as diplopia, increased orbital volume and enophthalmos, ocular movement restriction due to entrapment of extraocular muscles, infraorbital nerve paresthesia and blindness [4]. All reported cases had indication of surgical treatment due to presence of orbital defects larger than 2 cm^2, enophthalmos, diplopia and orbital content prolapse.

The goal of orbital reconstruction is to restore anatomy, volume and function. However, the visualization and adaptation of implants in posterior area defects can be difficult through palpebral approaches [3]. The use of endoscopy allow magnification and visualization of all surgical field [3]. Trapdoor fractures and small defects can be treated through endoscopic approach without skin incisions, but extensive defects require high technical sensitivity for placement of implants [5-6]. Therefore, due to the extension of the defects we use the combination between eyelid incision and transantral endoscopy to optimize the visualization and treatment of the patients.

The maxillary sinus represents an adjacent cavity to the orbital floor and can be used for endoscopic approach [7]. The use of 30-degrees endoscope may improve the orientation of surgeon and help to identify anatomical structures such as orbital floor and bone defects, prolapsed tissue, infraorbital nerve and maxillary sinus ostium [13]. In addition, the endoscope allows better understanding of the characteristics of the fracture and improve the adaptation of the implants [8].

The described combination of approaches shows few limitation or disadvantages. The possibility of obvious scars and complications in eyelid incisions are discussed in literature. However, complications are present in only 5% of cases and are less common in isolated orbital wall fractures [2]. In this case series was observed a transient excessive exposure of eye sclera. Transantral endoscopy complications are rare and related to their isolated use by inexperienced operator [4]. However, the antrostomy is associated to postoperative paresthesia and is contraindicated for children when the dental germs are present adjacent to a small maxillary sinus [5].

In this case series, the described technique allowed a simplified approach to orbital floor fractures, examination of defects extension and titanium mesh positioning. In all reconstructions the orbital volume was restored observing anatomical differences of up to 8% [9]. The greatest difference between the orbital volume was verified in patient #3. This patient had a zygomatic fracture involving the lateral wall which causes an increase of orbital volume. In addition, the increased volume is related to the major difference between the anteroposterior eyeball position observed in Table 1. However, all values are within the normal anatomical differences.

In conclusion, the combination of eyelid incision and transantral endoscopy is a simple and easy technique that allows to optimize the visualization and reconstruction of orbital floor. The postoperative CT scan analysis shows that all treatments restored orbital volume and globe position.

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Table 1. Patient and orbital characteristics, orbital volume and difference between the orbits.

Patient	Orbital volume (cm³)		Difference (%)	Difference of anteroposterior globe position (mm)
	Healthy orbit	Reconstructed orbit		
Patient #1	15.309	15.318	0.06	1.2
Patient #2	13.677	14.503	6.04	1.1
Patient #3	13.309	12.740	-4.28	-1.9

Figure 1. Endoscopic view of orbital floor fracture.

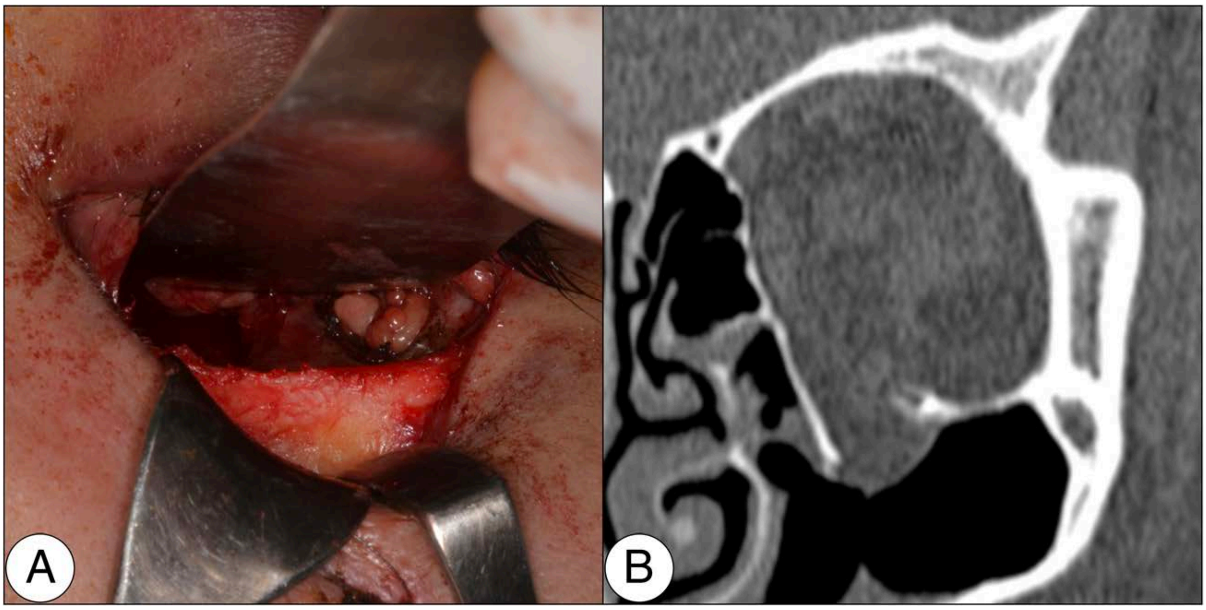
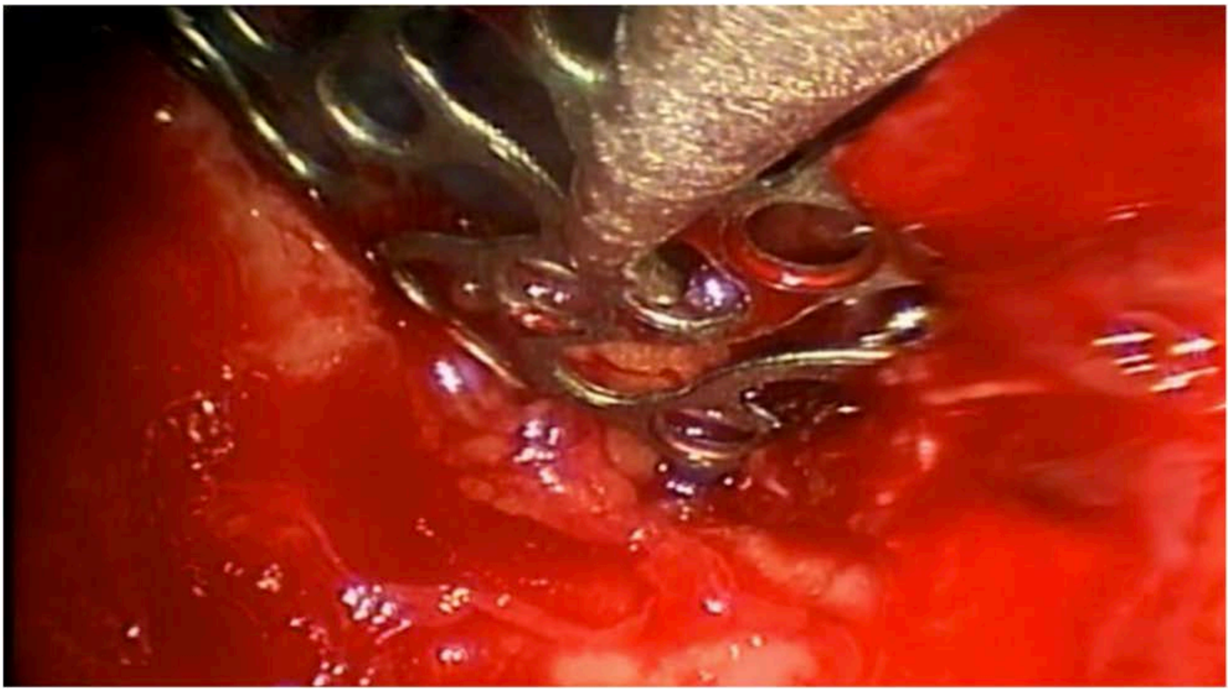


Figure 2. Endoscopic view of titanium mesh positioning and bone defect extension.



6 ARTIGO 4 – Three-dimensional printed model and transantral endoscopy to orbital fracture repair*

Three-Dimensional Printed Model and Transantral Endoscopy to Orbital Fracture Repair

Short title: Combined management to orbital fracture

Lucas Borin Moura[a], Pedro Henrique de Azambuja Carvalho[a], Marisa Aparecida Cabrini Gabrielli[a], Valfrido Antonio Pereira Filho[a]

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Abstract

Orbital fractures are high prevalent and result in several complications such as diplopia, muscular entrapment, visual impairment and enophthalmos. The goal of orbital reconstruction is to restore orbital anatomy, volume, and globe symmetry. This case report aims to describe the use of transantral endoscopy and 3D printed model for treatment of an orbital floor fracture. A 54-year-old woman presented orbital floor fracture with diplopia and extraocular muscle entrapment. The surgical treatment was performed using a standard titanium mesh bended over 3D printed model, and transantral endoscopy to verify fracture extension and implant adaptation. The postoperative evaluation demonstrates correction of diplopia and ocular motility restriction. CT scan showed reestablishment of the orbital anatomy. The association of transantral endoscopy and 3D printed models is a feasible technique to improve orbital reconstruction.

Key words: blowout fracture; endoscopic repair, orbital floor; three dimensional printing.

Introduction

Orbital fractures are highly prevalent in facial trauma and may result in several complications including diplopia, extraocular muscle entrapment, visual impairment, and enophthalmos (1,2). Treatment goal is to restore bone anatomy, orbital volume, soft tissue position, and the globe symmetry (3,4). Several materials are used for orbital reconstruction with success, however the shaping and adaptation in the posterior area can be challenging (5,6). The use of transantral endoscopy helps to verify the defect size and implant adaptation (5,6). Moreover, 3D printed models has been used to planning and implant pre-bending for orbital reconstruction (7).

Clinical Report

A 54-year-old woman was evaluated in the Division of Oral and Maxillofacial Surgery of São Paulo State University after a motorcycle accident. Initial examination showed left periorbital ecchymosis, isochoric pupils, preserved pupillary light reflex, and binocular diplopia with limitation of upper gaze in the left eye. CT scan demonstrated an orbital floor fracture with tissue herniation without inferior orbital fissure involvement (Figure 1a). Surgical planning was orbital reconstruction using prebent titanium mesh assisted by transantral endoscopy.

The 3D printed model was obtained from CT scan data. Preoperatively a standard titanium mesh (MODUS Mesh, Medartis®, Switzerland) was adapted to fit the 3D printed model and cover the orbital defect (Figure 1b). The surgical procedure was performed using a combination of intraoral and subciliary approaches. Transantral endoscopy was used to remove bone fragments and to verify the mesh adaptation in the posterior edge (Figure 1c). The postoperative period was uneventful, the diplopia and eye motility restriction were corrected. Hertel exophthalmometry measurement showed 1 mm of enophthalmos, and the postoperative CT scan demonstrate correct anatomic contour of the mesh (Figure 1d).

Discussion

The treatment of orbital fractures must restore the anatomy, volume , and function (5), however it can be challenging due to the complex tridimensional anatomy of the orbit (8). Therefore, the purposed surgical plan included the association of two techniques: transantral endoscopy and 3D printed model.

The visualization of all orbital defect is a key factor for success in orbital reconstruction. Thus, transantral endoscopy allows to improve magnification and visualization of the surgical field and implant adaptation (9). Moreover, it is possible to understand the characteristics of the fracture and amount of herniated tissue, also to remove bone fragments (5,10). The disadvantages are increased surgical time, learning curve, and necessity of another surgical approach (5,10).

In orbital fractures, patient-specific implants can be performed over the original or mirrored 3D printed model (4,7,8). Most of complications are associated with the incorrect orbital anatomy reestablishment, resulting in an increased orbital volume, enophthalmos and diplopia (4). Precise positioning and adaptation of the mesh is important to restore the orbital anatomy, especially when the posterior medial bulge is involved by the fracture (4). The use of 3D printed model allowed to pre-bend the titanium mesh according to the patient’s anatomy, and to cover all orbital defect.

Nowadays, 3D printers and endoscopes are more available at hospitals, and their use can improve orbital reconstruction outcomes with relative low cost, similar surgical time, and optimal visualization of fracture and implant. In the reported case the preoperative condition was solved using those tools.

Acknowledgments

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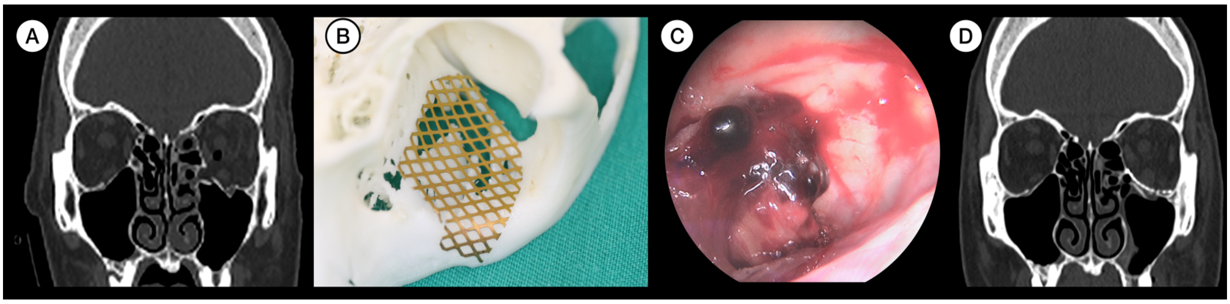
Figure 1. a. Preoperative CT scan. **b.** Titanium mesh bending in 3D printed model. **c.** Defect view through transantral endoscopy. **d.** Postoperative CT scan.



7 CONCLUSÃO

A partir da metodologia aplicada nesta série de estudos foi possível concluir que:

1) A reconstrução orbitária por meio de malhas de titânio convencionais reestabeleceu o volume orbitário e a posição tomográfica anteroposterior do globo ocular, independentemente do tipo e da severidade do defeito orbitário presente;
2) Ambos os métodos para análise do volume orbitário, segmentação automática e seccionamento de imagens, se apresentaram viáveis;
3) A metodologia aplicada para segmentação de estruturas orbitárias por meio de exames tomográficos e de ressonância magnética permitiu a confecção de um modelo digital da completo cavidade orbitária;
4) A análise por meio de elementos finitos verificou que o mecanismo hidráulico resulta em uma pequena área de estresse na parede medial, enquanto que o mecanismo de trauma direto ao rebordo resulta em uma grande área de estresse no assoalho orbitário;
5) A gordura orbitária e os músculos extraoculares tem um papel importante na absorção das forças e na distribuição para as paredes orbitárias;
6) Para a otimização do tratamento de fraturas orbitárias, técnicas adjuntas como endoscopia transantral e modelos tridimensionais podem ser utilizadas;
7) A endoscopia permitiu a visualização de todos os bordos do defeito orbitário no assoalho, assim como a verificação do correto posicionamento da malha de titânio;
8) O modelo impresso permitiu a melhor conformação e adaptação da malha de titânio.

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ANEXO A – Aprovação do Comitê de Ética (CEP)

FACULDADE DE ODONTOLOGIA DE ARARAQUARA - UNESP

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Avaliação volumétrica de fraturas orbitárias unilaterais tratadas por meio de malhas de titânio - Estudo Retrospectivo

Pesquisador: Valfrido Antonio Pereira Filho

Área Temática:

Versão: 4

CAAE: 44029115.9.0000.5416

Instituição Proponente: Faculdade de Odontologia de Araraquara - UNESP

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 1.220.481

Apresentação do Projeto:

O projeto intitulado " Avaliação volumétrica de fraturas orbitárias unilaterais tratadas por meio de malhas de titânio- Estudo retrospectivo" é classificado como um estudo retrospectivo usando 60 tomografias de pacientes que tiveram fraturas orbitárias unilaterais tratadas por malha de titânio, sendo avaliados os volumes orbitários das duas órbitas, íntegra e reconstituída. Pretende testar a hipótese de que reconstruções de fraturas orbitárias tratadas por malhas de titânio atingem o objetivo de restabelecimento do volume orbitário. Os critérios de inclusão e de exclusão estão bem definidos e o delineamento experimental adequado.

Objetivo da Pesquisa:

Avaliar por meio de tomografias pertencentes ao banco de imagens da Disciplina de CTBMF- FOAr – Unesp, o volume de cavidades orbitárias de pacientes com fraturas orbitárias unilaterais envolvendo uma ou mais paredes, submetidos a reconstrução cirúrgica por meio de malhas de titânio.

Avaliação dos Riscos e Benefícios:

Avaliação dos Riscos: O único risco que pode existir é a exposição da identidade dos pacientes entretanto o pesquisador garante que para a análise volumétrica das órbitas através de tomografias, a identidade dos pacientes será preservada. Neste tipo de análise não existem riscos

para o pesquisador.
Benefícios : Não haverá benefícios diretos para os pacientes já tratados, mas os resultados desta pesquisa poderão beneficiar pacientes tratados por este método no futuro.

Comentários e Considerações sobre a Pesquisa:

O desenho experimental e a metodologia que será utilizada foram apresentados de modo objetivo, mostrando que o trabalho será realizado dentro das normas éticas.

Considerações sobre os Termos de apresentação obrigatória:

O pesquisador solicitou e justificou a dispensa do Termo de Consentimento Livre e Esclarecido, adequou os termos.

Conclusões ou Pendências e Lista de Inadequações:

Não existem pendências.

Considerações Finais a critério do CEP:

Protocolo APROVADO em reunião de 09 de Setembro de 2015.
O pesquisador deverá encaminhar relatórios parciais a cada 01 (um) ano até o prazo final da pesquisa, quando deverá encaminhar o relatório final.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Declaração de Instituição e Infraestrutura	Banco Imagens.pdf	12/03/2015 16:52:52		Aceito
Outros	Ressarcimento gastos.pdf	12/03/2015 16:55:23		Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_479035.pdf	12/03/2015 17:52:18		Aceito
Outros	Termo de Cumprimento.pdf	30/03/2015 10:27:43		Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_479035.pdf	30/03/2015 10:29:07		Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_479035.pdf	13/05/2015 13:00:57		Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_479035.pdf	30/06/2015 09:47:27		Aceito
Projeto Detalhado / Brochura Investigador	Projeto Lucas Borin-2015.pdf	13/08/2015 18:05:14		Aceito

Outros	Solicitação dispensa do TCLE.pdf	13/08/2015 18:06:13		Aceito
Folha de Rosto	Folha Rosto.pdf	13/08/2015 18:05:06		Aceito
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_479035.pdf	13/08/2015 18:07:15		Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

ARARAQUARA, 09 de Setembro de 2015

Assinado por:
Lígia Antunes Pereira Pinelli
(Coordenador)

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