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YULI ANDREA LOPEZ QUINTERO

SIMULAÇÃO DINÂMICA DE PROJÉTEIS DISPARADOS CONTRA A REGIÃO OCCIPITAL DO CRÂNIO HUMANO – ANÁLISE DE ELEMENTOS FINITOS

DYNAMIC SIMULATION OF BULLETS FIRED AT THE OCCIPITAL REGION OF THE HUMAN SKULL - FINITE ELEMENT ANALYSIS

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Dissertação apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Mestre em Biologia Buco-Dental, na área de Odontologia Legal e Deontologia.

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Orientador: Prof. Dr. Felippe Bevilacqua Prado
Coorientador: Prof. Dr. Alexandre Rodrigues Freire

Este exemplar corresponde à versão final da dissertação defendida pelo aluno Yuli Andrea López Quintero, orientada pelo Prof. Dr. Felippe Bevilacqua Prado e coorientada pelo Prof. Dr. Alexandre Rodrigues Freire.

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RESUMO

Feridas por arma de fogo na região occipital são conhecidas em casos de execução. O aumento da violência armada nos últimos tempos tem exigido estudos que investiguem os padrões de destruição do tecido ósseo com o intuito de conhecer os mecanismos de lesão, reconstruir os eventos em torno da morte através de uma adequada interpretação da possível distância, velocidade, direção e tamanho do calibre do projétil. A avaliação desta natureza de ferimentos tem sua importância nas investigações policiais e criminalísticas no âmbito forense. O objetivo deste estudo foi simular caraterizar os impactos de projéteis de arma de fogo na região do osso occipital por meio da análise de elementos finitos. As imagens tomográficas de um crânio humano, adulto, seco, teve sua estrutura óssea segmentadano software Mimics v. 18. Após segmentação, no software Rhinoceros® 3D 5.0 foi obtida a geometria do crânio. Os projéteis utilizados neste estudo foram: .380 Auto, .40 S&W, 9 mm Luger. As geometrias de cada projétilfoi obtida no software Rhinoceros® 3D 5.0. A construção do modelo de elementos finitos foi realizada no software Ansys v16. Todas as estruturas foram consideradas lineares e elásticas. A estrutura óssea foi considerada isotrópica. Nas condições de carregamento foram configuradas as velocidades, angulação e distâncias dos projéteis, tudo por meio computacional em análise dinâmica. A única variável de interferência no projétil considerada foi a força da gravidade no valor de 9,8 m/s2. A distância definida entre o osso occipital e os projéteis foi de 5 centímetros. Essa distância corresponde, teoricamente, ao espaço virtual entre a boca do cano de uma arma do calibre estudado e o osso, caracterizando um tiro a curta distância. Nos resultados, foi analisada a tensão equivalente de von Mises, bem como a morfologia do orifício de entrada produzido pela entrada de cada projétil. Os padrões de ferimentos observados nos diferentes calibres estudados mostraram um aspecto oval, em que o .40 ficou mais perto ao circular. A maxima de tensão de von Mises observada foi de 181.6 MPa para a 9mm, 121,25 MPa no .380 e 88.83 MPa no .40. As simulações realizadas possibilitaram a caracterização das feridas após a penetração dos diferentes projéteis no osso occipital.

Palavras-chave: Análise de Elementos Finitos.Ciências Forenses.Balística. Osso Occipital.

ABSTRACT

Gunshot wounds in occipital region are commonly found execution cases. The increase of the violence in the last times has required studies to investigate destruction patterns in bone tissue in order to know the mechanism of the injuries, reconstruct the events surrounding death through a proper interpretation of the possible distance, velocity, direction and bullet caliber size of the firearm used. The nature and evaluation of the different types of wounds are important to police and criminal investigations in the forensic context. The aim of this work was to characterize the impact of firearm bullets in the occipital bone region through finite element analysis. The tomographic images of a human dry skull, adult, had the bone structure segmented on the Mimics software v. 18. After segmentation, the geometry of the skull was gathered on the Rhinoceros® 3D 5.0 software. The bullets used in this study were: .380 Auto, .40 S&W, 9 mm Luger. The bullets geometry was gathered on the Rhinoceros® 3D 5.0 software. The Finite Element Model construction was carried out in the Ansys v16 software. All structures were considered as linear and elastic. The bone structure was considered isotropic. In the loading conditions were configured the velocities, angle and distances of the bullets, everything by computational means in dynamic analysis. The gravity with value of 9.8 m/s2 was considered like the only interference variable on the trajectory of the bullet. The distance between the occipital bone and the projectiles was 5 cm. These distances correspond, theoretically, to the virtual space between the gun muzzle and the bone, featuring a shot from close range. In the results, the von Mises stress and the morphology of the inlet orifice to each projectile was parsed. The wounds patterns observed to the different calibers showed an oval aspect, wherein .40 was closer to circular. The maximum value of von Mises stress was 181.6 Mpa to 9 mm, 121.25 MPa to .380 and 88.83 MPa to .40. The simulations allowed the characterization of the wounded after the penetration of the bullets in the occipital bone.

Key words: Finite element analysis. Forensic Sciences. Ballistic. Occipital bone.

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1 INTRODUÇÃO

Os diferentes tipos de violência podem ser classificados em três grandes grupos, a saber: autodirigida (como no suicídio ou automutilação), coletiva (em atos de guerra ou por gangues) e interpessoal (contra crianças, pessoas idosas, conhecidos) (Souza, et al., 2014). Miller, et al., (2007) relatam que dois em cada três vítimas americanas de homicídio são mortas com armas de fogo. Entre as regiões do corpo mais atingidas por feridas com armas de fogo tem-se a cabeça (44,5%), tórax (25,7%), abdôme (10,7%), e a coluna vertebral (5,7%) (Papadopoulos, et al., 2013). Um estudo de cinco anos (1998 a 2003) no Estado de Rivers, na Nigéria, revelou que lesões na cabeça são a causa mais comum da morte, especialmente em acidentes de trânsito, tiro de arma de fogo e assalto, respetivamente (Seleye-Fubara & Etebu, 2011).

Gore, et al., (2003) investigaram, retrospectivamente, 444 mortes por arma de fogo em Diyarbakir - Turquia, indivíduos autopsiados pelo Conselho de Medicina Legal num período de 6 anos (1996 a 2001), incluindo homicídio (296 casos, 66,7%), suicídio (120 casos, 27%) e tiroteios acidentais (28 casos, 6,3%). No homicídio encontraram que a cabeça foi o local de maior frequência, respondendo por 82 (68,3%) dos óbitos, e concluíram que os fatores que contribuem para o aumento da morte por arma de fogo são as atividades dos terroristas, hábitos tradicionais de obtenção e uso de armas de fogo e gangues de sangue. Kaptigau, et al., (2007) relataram que o uso de objetos contundentes, armas de fogo e flechas, juntamente com o aumento da violência urbana é responsável pela maior parte das lesões em crânio.

O incremento da violência no Brasil afeta a mortalidade e a mobilidade da sua população, Souza, et al., (2014) analisaram a taxa de mortalidade por homicídio no estado da Bahia mediante dados do sistema de informação sobre mortalidade (SIM). Estes autores evidenciaram a relação da referida violência com a baixa escolaridade, Gawryszewski, et al., (2005) reportaram diferentes fontes de dados de homicídios por meio de certidões de óbito, laudos de médicos legistas e boletins de ocorrência policiais de residentes vinculados à cidade de São Paulo, para o segundo semestre de 2001, mostrando como resultado uma taxa bruta de homicídios de 57,2 / 100.000, sendo a proporção de homicídios por armas de fogo de 88,6%, e a maioria destas lesões foram na cabeça (68,9%), Freitas & Bonatelli (2000) estudaram 417 ferimentos crâneo-encefálicos que foram produzidos por um único projetil o qual mostrou uma taxa de mortalidade de 63,1% (n=263), já Souza, et al., (2013) mediante o análise de 181 prontuários de indivíduos com traumatismo crâneo-encefálico por projétil de arma de fogo da Santa Casa de São Paulo encontraram que o mais atingido foi o sexo masculino com um 85%

(n=154) e o sexo feminino em um 15% (n=27), em quanto as regiões encefálicas mais acometidas foram o lobo frontal (27,6%), seguido pelo temporal (24,86%) e occipital (16,57%), avaliados em um período de 16 anos (1991-2005).

Estudos foram realizados com o intuito de encontrar uma correlação direta entre arma-projétil e o diâmetro da ferida, a morfologia, a contaminação e a destruição dos tecidos (Berryman, et al., 1995) (Stuehmer, et al., 2009) (Matoso, et al., 2014). Plattner, et al., (2003) estudaram a reprodução da forma e o padrão de resíduos por arma de fogo perto das feridas através de uma série de disparos experimentais sobre a pele em um modelo de tecido mole, Ozer, et al., (2007) mostraram os efeitos de diferentes tiros em tecidos do corpo com o objetivo de conhecer o tipo de arma que causou o dano e as suas características, Von See, et al., (2009) dispararam na cabeça de porcos com 5 projéteiscom a mesma energia cinética e encontraram diferenças consideráveis nos padrões de lesões entre eles. Cecchetto, et al., (2011) avaliaram por meio de micro-CT ferimentos de projétil de alcance intermédio acoplado a um software de análise de imagem, a fim de quantificar as partículas de pó e determinar a distância do tiro em secções de pele obtida a partir de pernas humanas amputadas cirurgicamente.

Feridas por armas de fogo na região occipital são conhecidas em casos de execução (Matoso, et al., 2014), sendo consideradas uma forma frequente de lesão fatal (Leymann & Althoff, 1980), a qual tem como característica o uso de armas de pequeno porte disparadas a curta distância (Szleszkowski, et al., 2014). Este tipo de ferimento também tem sido referido como fonte mais comum de injúrias em homicídios relacionados com gangues na população adulta (Aryan, et al., 2005) (Stone, et al., 1995) e em crianças e adolescentes (Levy, et al., 1993).

Szleszkowski, et al., (2014) realizaram um estudo em 194 restos esqueléticos dos quais 108 foram determinadas as causas da morte sendo em sua maioria (76 casos) tiros na região occipital relacionados com execução, na cidade de Warsaw na Polônia, neste estudo também são reportados casos de exumações com o mesmo tipo de ferimento em cidades tais como Katyn, Kharkov e Mednoye; Szleszkowski, et al., (2014) analisaram os restos mortais de 23 indivíduos com a mesma caraterística de ferimento de execução na região occipital os quais foram recuperados do Cemitério Osobowicki em Wroclaw (Polónia), no campo 83B no 2012 (Szleszkowski, et al., 2012). Em 1948 e 1949, Slaus, et al., (2007) realizaram a identificação e análise de 61 restos humanos recuperados de poços na croácia da guerra de 1991, nos quais observaram uma frequência significativamente maior de feridas de bala sugestivas de execução no osso occipital reportando 44,1%.

Casos de tiros na região occipital com caraterísticas de execução tem sido reportados por Zugibe & Costello (1993), Feinsod (2003), Ran, et al., (2010) em combates, Rothschild & Schneider (2000) após um assalto, D'Errico, et al., (2011) pela máfia italiana, o que mostra o alto índice deste tipo de ferida nesta região.

Modelos precisos da cabeça humana têm sido desenvolvidos para avaliar diferentes tipos de lesões e validados com experiências reais sobre o movimento cerebral localizado, aceleração intracerebral e a pressão intracraniana, cujas comparações com os resultados previstos pelo modelo foram satisfatórias (Panzer, et al., 2012) (Mao, et al., 2013) (Zhu, et al., 2013). Diferentes partes da cabeça foram testadas a impactos em ossos frontal (Matoso, et al., 2014), temporal e parietal (Singh, et al., 2014) variando direções de carga e duração de impacto incluindo a região occipital (Chu, et al., 1994) (Yoganandan, et al., 1995) (Kleiven, 2006) (Monea, et al., 2014). Forças de esmagamento também foram recriadas no crânio aplicando pressões bilaterais nas regiões correspondentes (Baumer, et al., 2010). Aomura, et al., (2003) realizaram um teste de colisão usando um pêndulo com um bloco de ferro impactando um modelo físico na região occipital incluindo o pescoço humano, o resultado do ensaio e o resultado do cálculo numérico fornecido pelo modelo de elementos finitos obtiveram uma boa concordância.

A análise de elementos finitos tem mostrado sua utilidade em diferentes tipos de injúrias por meio da sua análise dinâmica, buscando estabelecer critérios de identificação de lesões que indiquem padrões e relacionamentos entre prováveis agentes-receptores (Raul, et al., 2006). Usando estes modelos nas reconstruções forenses tem sido identificadas condições de impacto mecânicos-dinâmicos e formações de fraturas a partir de caraterísticas de variabilidade biológica tais como geometria, espessura, rigidez, número de suturas e densidade do crânio (Thollon, et al., 2013).

Os Modelos de Elementos Finitos tridimensionais têm permitido explorar o grau dos danos crêneo-encefálicos ocasionados como resultado de uma queda a diferentes distâncias reproduzindo situações acidentais tais como quedas desde um prédio em construção, ciclistas ou pedestres, neste são analisadas as distribuições das tensões e deformações no crânio (Ruan, et al., 1994) (Lei, et al., 2009) (Liu, et al., 2013) (Monea, et al., 2014), assim como na área clínica na elaboração de dispositivos de fixação occipitocervicalpara fornecer uma base teórica para a aplicação clínica (Cai, et al., 2014). Coats, et al., (2007) estudaram o impacto da cabeça de um bebê no osso occipital a uma distância de 0.3m contra o concreto.

Desta forma, a associação entre o conjunto de conhecimentos técnico-científicos e criminalísticos ajudam a reestabelecer lesões ou mortes causadas por projéteis, que é de interesse nesta pesquisa. A caraterização das caraterísticas de ferida por projéteis é uma questão importante para interpretar distância, velocidade, alcance, efeito, direção e às vezes o tamanho do calibre, circunstâncias que ajudam ou orientam as investigações policiais e ou judicias contribuindo como elementos probatórios no momento de estabelecer um fato delitivo (Quatrehomme & Iscan, 1998) (Quatrehomme & Iscan, 1999), assim como na confecção de capacetes à prova de bala com o fim de impedir lesões e mortes em combates (Ran, et al., 2010), além da possibilidade de fornecer aos cirurgiões de cabeça e pescoço uma ajuda para o melhoramento das técnicas cirúrgicas (Doctor & Farwell, 2007).

Execução por ferimento de arma de fogo em osso occipital pode ter variações na sua morfologia devido a fatores como a arma de fogo e o calibre do projétil utilizados, a distância do atirador ao alvo, diferentes ângulos representando como o assassino empunhe a arma em direção à vítima e a posição em que esta última possa estar (em pé, deitado de bruços, ajoelhado). O presente estudo investigou os padrões de destruição do tecido ósseo numa avaliação dinâmica utilizando a análise elementos finitos, para melhorar a compreensão dos mecanismos de lesão, reconstruir os eventos em torno da morte, e para a possível criação de critérios de ferimentos nesta região com o fim de facilitar as investigações policiais e criminalísticas no âmbito forense.

2 ARTIGO

Characterization of Gunshot Wound in the Occipital Bone Region Using Finite Element Dynamic Simulation

Artigo submetido ao periódico: PLOS ONE Journal (Anexo 2)

Autores: Yuli Andrea López Quintero, Alexandre Rodrigues Freire, Ana Cláudia Rossi, Rodrigo Ivo Matoso, Felippe Bevilacqua Prado.

Abstract

Gunshot wounds in the occipital region are commonly found in execution cases. The recent increases in violence warrant studies to investigate the destruction patterns in bone tissue and thereby understand the mechanisms underlying the injuries and to reconstruct the events surrounding a death through the proper interpretation of the possible distance, velocity, direction and bullet caliber size. The characterization and evaluation of different types of wounds are important for police and criminal investigations in the forensic context. The aim of this work was to simulate the impact of firearm bullets in the occipital bone region by using finite element analysis. Tomographic images were obtained of a human dry skull from an adult, and the bone structure was segmented using the Mimics v18 program. After segmentation, the geometry of the skull was evaluated using the Rhinoceros® 3D 5.0 software. The bullets used in this study were a .380 Auto, .40 S&W, and 9 mm Luger. The bullet geometry was also determined using the Rhinoceros® 3D 5.0 software. The Finite Element Model construction was carried out using the Ansys v16 software. The bone structure was considered to be isotropic. The loading conditions were configured based on the velocities, angle and distances of the bullets in the dynamic analysis. The distance between the occipital bone and the projectiles was 5 cm. This distance corresponds, theoretically, to the virtual space between the gun muzzle and the bone. The von Mises stress and the morphology of the inlet orifice following exposure to each projectile was parsed. The wound patterns observed for the different calibers showed an oval aspect, with the .40 having a pattern that was closer to circular. The maximum value of the von Mises stress was 181.6

MPa for the 9 mm, 121.25 MPa for the .380 and 88.83 MPa for the .40. The simulations allowed for the characterization of the wounds after the penetration of the bullets in the occipital bone.

Key words: Finite element analysis; Forensic sciences; Ballistic; Occipital bone.

Introduction

Mechanical, physical, chemical and biological agents, among others, contribute to the loss of life or health of an individual [1]. The frequent use of firearms has highlighted the mechanical effects that occur under different situations: homicides, suicides, robberies, shootings, executions, legal interventions, unintentional deaths, deaths due to unknown or undetermined causes and so forth [2-7].

Among the regions of the body, the head (44.5%), thorax (25.7%), abdomen (10.7%) and vertebral column (5.7%) were the most common injuries caused by firearms in Athens, Greece [7]. In cases of murder reported in Diyarbakir, Turkey, the head was the preferred location, accounting for 68.3% of such deaths [4]. In Rivers State in Nigeria, head injuries produced by firearms were found to be the most common cause of death, accounting for 23.5% of firearm-related deaths [8]. In Puerto Moresby, Papua Nueva Guinea, 340 cranial injuries were reported, 14% of which were penetrating skull fractures and open depressed fractures, accounting for 4 of every 7 deaths from [9].

In Brazil, several studies have shown similar findings. For example, in Porto Alegre state, a total of 417 patients with skull-encephalic injuries produced by a single projectile showed a mortality rate of 63.1% [10]. In São Paulo state,2,714 homicides were reported for the second half of 2001, with most of these caused by firearms (88.6%), and most of the homicides (68.9%) were by head injuries [11]. An analysis of 181 records from Santa Casa in São Paulo evaluated from a period of 16 years showed that the brain regions most commonly affected by firearms were the frontal lobe (affected in 27.6% of cases), followed by the temporal (24.86%) and occipital (16.57%) regions [12].

Wounds in the occipital region caused by firearms are common in execution cases [13], with most cases killed using handguns fired at close range [14]. These injuries are generally fatal [15]. In Los Angeles, USA, handguns were found to be the main cause of gang-related homicides in the adult population. Of the 525 recorded victims, 51% were associated with such organizations, and 30% of these used a shot in the occipital region as a method of execution [16]. In contrast, of 105 other victims, including children and adolescents, 72% of the killings were associated with gangs, and 28% had been shot in the occipital region [17]. In Poland a gunshot to the occipital region was reported as a method used to execute hostages. Of the 108 people executed in Warsaw, 70.4% had an occipital wound [18]. In a report from Wroclaw, from 223 victims, 17.48% of the 223 victims showed the same features [19]. In another region of the same city, 23 bodies were found, and 47.82% presented with the same type of injury [14, 20]. In Hubertus, 41 similar cases were reported [21]. In Croatia, 61 bodies were found in dry wells, and 1,111 bodies were found in functioning wells, 44.1% and 15.1% of which, respectively, exhibited typical signs of this type of execution [22].

Previous studies have been performed to find a direct relationship between the between the projectile and the wound diameter, morphology, contamination, tissue destruction, gunshot pattern residues and particle quantification. Therefore, experimental and computational techniques have been used in attempts to identify the weapon type that caused the damage, differences in the patterns of injuries and to determine the shooting distance. Experiments have been performed in (a) animal parts, such as pig heads [23] and calfskin fixed to a gelatin block or soup [24], (b) patients or autopsy cases [25-27], (c) skin sections from surgically amputated human legs [28], and (d) soft tissues of the body and ballistic gel candles [29]. Finite Element Analysis was used to determine these characteristics computationally in many of these studies [13, 30-37].

The aim of the present study was to evaluate the morphological and morphometric features of wounds after a bullet has penetrated the occipital bone. This study was conducted using three different calibers of bullets in an explicit dynamic simulation.

Materials and Methods

The Committee for Ethics in Research of the State University of Campinas (Protocol number -123/2015) approved this research.

For this research, we considered the conditions of an execution, where the victim is kneeling, head inclined and looking at the floor, while the shooter is standing behind the victim. In this situation, the projectile enters perpendicular to the skull in the occipital region. The simulation parameters of the shooting conditions were then established for (a) the firearm caliber and (b) the shooting distance.

1. Sample acquisition

In this study, we used images with a 0.25-mm slice thickness that were obtained using cone beam computed tomography of a dry skull from the Laboratory of Anatomy of Piracicaba Dental School, State University of Campinas, SP, Brazil.

2. Geometrical construction

The three-dimensional set of contiguous sectional images was presented in gray scale, where each value on the scale corresponds to an intensity value in the voxel. The Materialise MIMICS v.18 program (Materialise, Leuven, Belgium) was used for the segmentation of the cone beam computed tomography images. After segmentation, a three-dimensional surface in a stereolithographic (STL) format was created (Fig 1). The STL images from the skull were imported into the Rhinoceros 5.0 software (McNeel & Associates, Seattle, WA, USA), where the geometrical modeling was performed (Fig 1).

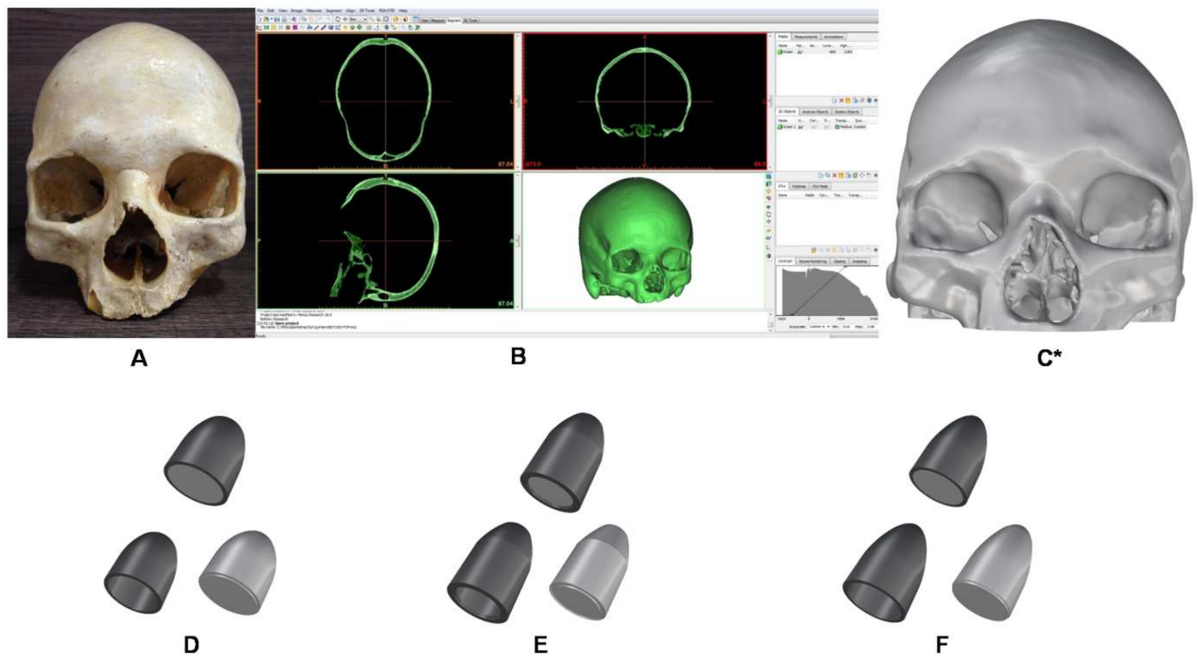

Fig 1. Steps performed for human skull modeling showing (A) the dry human skull (real), (B) the segmentation using the MIMICS v18 software and (C) the final geometry obtained through reverse engineering modeling (*After the inferior plane was cut to restrict the application during the simulation) The geometries of the bullets (D) .380, (E) .40 and (F) 9 mm were obtained using the Rhinoceros 5.0 software.

The geometries of the bullets were also obtained using the Rhinoceros 5.0 software (McNeel & Associates, Seattle, WA, USA) (Fig 1). Three bullets were modeled following the design of .40, .380 and 9 mm calibers (Table 1). The technical information (dimensions) for the construction of the geometries of the bullets was provided by Mr. Ivan Moraes Gasparotti from Cartridges Brazilian Company (CBC, Ribeirão Pires, SP, Brazil).

Table 1. Bullet features according totheir material composition and recommended utilization according the Cartridges Brazilian Company (CBC, Ribeirão Pires, SP, Brazil)

Bullets	Features	Recommended Utilization
.380 Auto	full metal-jacketed; round nose	Great penetration into barricaded targets
.40 S&W	full metal-jacketed; flat point	Great penetration into barricaded targets
9 mm Luger	full metal-jacketed; round nose	Military use with great penetration

3. Finite element model construction

The geometry of the human skull was imported into the ANSYS v16 (ANSYS, Inc., USA) software, in which a three-dimensional finite element mesh was constructed using our custom mesh generator software. The final mesh was composed of tetrahedral elements (Fig 2) and an average element quality of 0.79 (SD ± 0.12), where 0 was the worst value and 1 was the best. At the bullet impact region, the mesh was refined for better accuracy in the results (Fig 2).

All structures were considered linear and elastic. The bone structure and material of the projectiles were considered isotropic [38-39]. These properties were in agreement with the elastic modulus values (E) and Poisson's ratio (v) of isotropic structures. All structures were continuous. The mechanical properties of the bone structure are shown in Table 2.

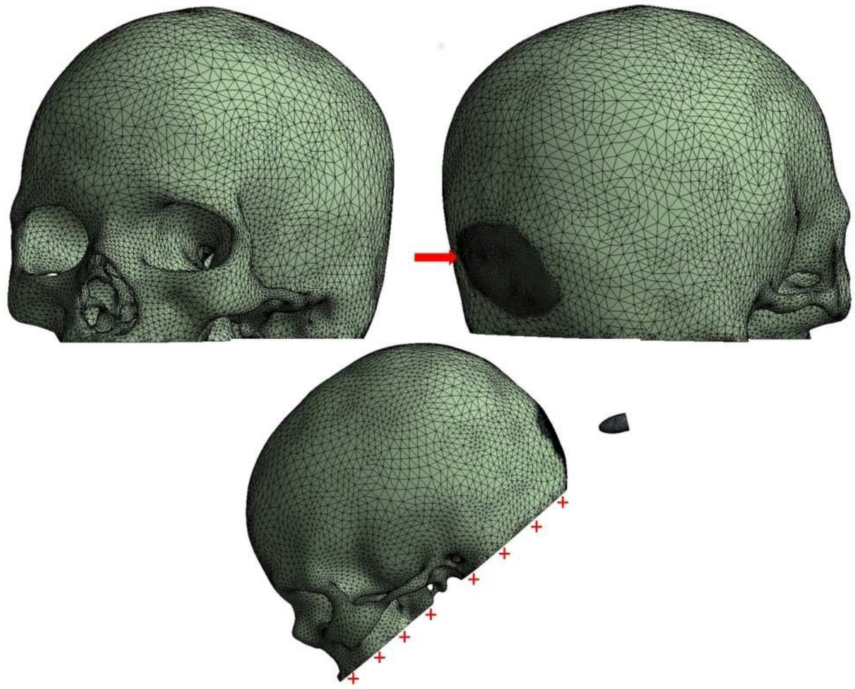

Fig 2. Finite element mesh with tetrahedral elements (ANSYS v16 software; ANSYS, Inc., USA). The red arrow indicates the region with refinement.

Table 2. Mechanical properties of bone

Materials	Modulus of Elasticity (E)*	Poisson's ratio(*v*)
Bone	14	0.3

[38-39] *Values in gigapascals (GPa).

The mechanical properties of the bullets in the finite element model were assigned according to predetermined data to compute the dynamic analysis [40]. These properties are described in Table 3 (CBC, 2011).

Table 3. The mechanical properties of the different calibers of bullets.

Properties of the materials	.380-caliber		.40-caliber S&W		9 mm Luger	
	Jacket (Cu^b)	Core Pb (99%) and Sb (1%)[c]	Jacket (Cu^d)	Core Pb (99%) and Sb (1%)[c]	Jacket (Cu^d)	Core Pb (99%) and Sb (1%)[c]
Elasticity modulus (GPa)	115	14	115	14	115	14
Poisson's ratio	0,3	0,38	0,3	0,38	0,3	0,38

b. Copper alloy UNS C23000 [57] (MatWeb, 2012c)
c. Alloy containing 99% lead and 1% antimony [57] (MatWeb, 2012b)
d. Copper alloy UNS C22000 [57] (MatWeb, 2012a)

4. Analytical configuration

In the explicit dynamics conditions, the analysis was configured to assess the impact of the bullets on the occipital bone. The initial velocity of the bullet was set according to the velocity to determine when it exited the muzzle. In addition, the angle and distance of the bullets were determined by using the position from which they exited the muzzle, and these were considered in the geometrical modeling. The only external variable of interference during the bullet displacement was the standard earth gravity (9.8 m/s^2).

The velocity values made available by the Cartridges Brazilian Company [40] for the .380 caliber, .40 caliber S&W and 9x19 mm Luger are shown in Table 4 (CBC, 2011).

Table 4. Kinematic data for when the bullets exit the muzzle

Bullets	Velocity (m/s)	Weight (g)	Energy (Joules)
.380 Auto	308	95	293
.40 S&W	300	180	524
9 mm Luger	332	124	443

The distance between the occipital bone and the bullets was equal to 5 cm. This distance theoretically corresponds to the virtual space from the muzzle of the gun being studied to the bone, representing a close-range shooting (Fig 3).

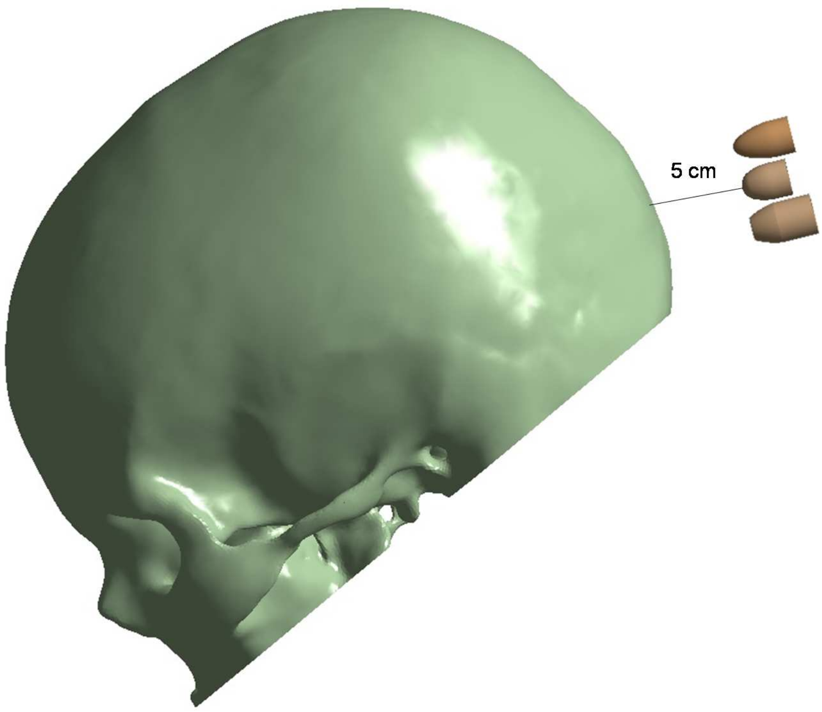

Fig 3. Configuration used for the analysis showing the distance of the bullets from the bone and the boundary condition (restraints indicated by red crosses).

A cut plane at the skull base level was created to apply restraints in all axes (Fig 3). This boundary condition allowed for greater stability during the simulation.

Measurements of the horizontal and vertical diameters of the outer edges of the wound were made using the ImageLab 2000 software. The images were obtained from the results included in the Ansys software, which contained the wound area and a reference scale (in mm). Thus, after the calibration, the horizontal and vertical diameters were measured to determine the morphometric differences between wounds caused by the different calibers of bullets.

Results

In this work, the different morphological patterns of the wound orifice and the stresses produced in the inlet orifice (von Mises criteria) were observed for three different calibers of bullets.

1. Injury patterns

The injury patterns were observed according to the morphological characteristics of the inlet orifice, which included the apparent shape and the horizontal and vertical diameters (Table 5). All of the inlet orifices presented an oval shape that was close to circular. The most circular shape was formed from the .40 caliber impact.

Table 5. Morphometric measurements and maximum stress of the wound

Sample		**Results**		
	Shape	Horizontal diameter (mm)	Vertical diameter (mm)	Maximum stress in the wound (MPa)
.380 bullet	Oval	13.94	14.85	121.25
.40 bullet	Circular	15.30	15.15	88.837
9 mm bullet	Oval	16.62	15.71	181.63

The inlet orifice caused by the .380 bullet penetration was oval but very close to circular, with a vertical diameter greater than the horizontal diameter (Table 5). The orifice caused by the .40 bullet had a circular shape, which presented smaller differences between the vertical and horizontal diameters. The impact from the 9 mm Luger bullet produced an oval inlet orifice, which was very close to circular, with small extensions in the lateral direction. The horizontal diameter was greater than the vertical.

2. von Mises stress in the impact region

The von Mises theory considers the distortion energy of one side of the element, or the energy associated with changes in the element shape, but not the element volume. If the geometric combination of all tensions acting on a specific point of a ductile material exceeds the traction resistance, the material breaks in that location [41]. In this study, the energy supplied by the projectile's penetration into the skull (Fig 4), the stress condition values, and the deformation that led the material to fail (rupture or leak) were parsed in each sub-region determined by the finite elements.

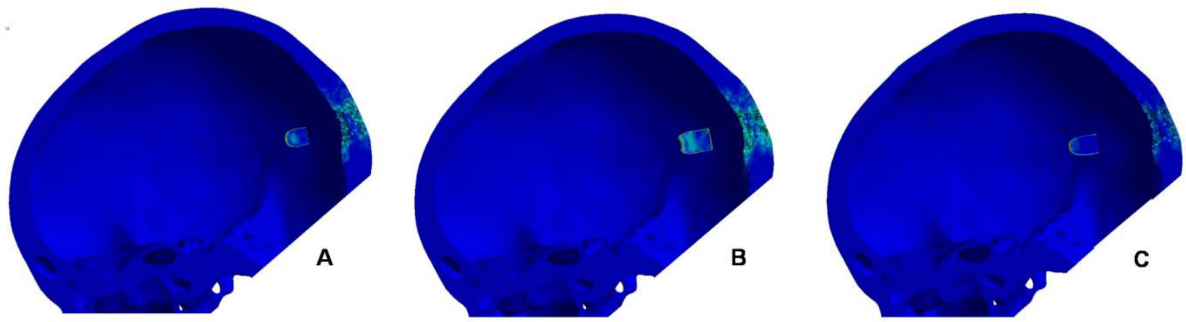

Fig 4. Results showing the von Mises stress and the bone destruction after bullet penetration. This sagittal plane shows the differences between the external and internal bone destruction caused by energy dissipation from the bullets (A) .380, (B) .40 and (C) 9 mm.

The entire wound (external and internal bone surface) caused by the .380 bullet showed a maximum stress of 121.25 MPa. The stress was distributed over the entire wound edge but was focused at the superior region. From the wound edge, the stress dissipated to the adjacent surface in the occipital bone, which presented low stress values (Fig 5A).

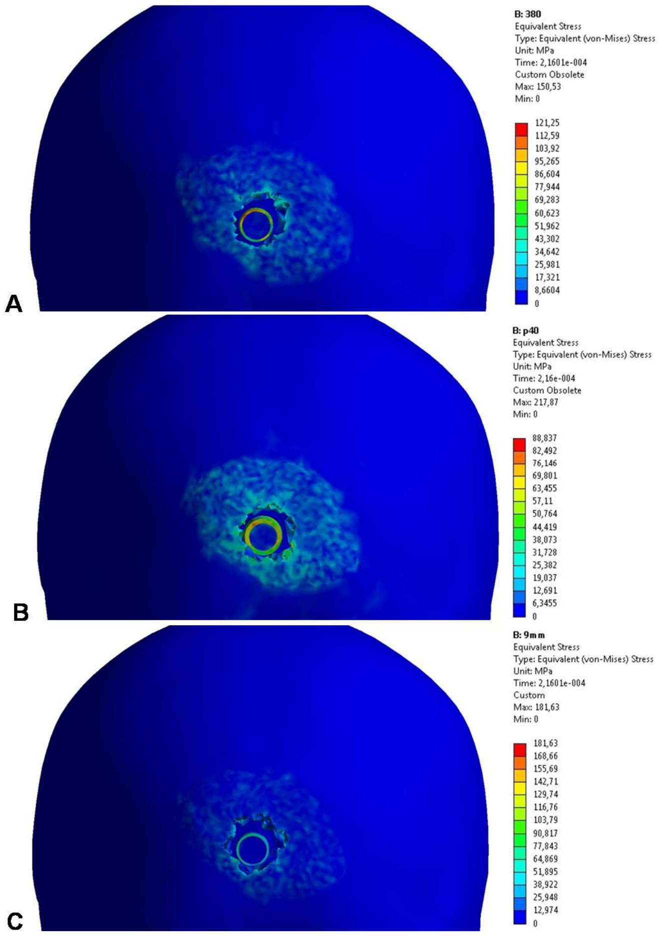

Fig 5. von Mises stress after the penetration of the three bullets (A) .380, (B) .40 and (C) 9 mm. The stress values in the scale were applied to the bone structure.

The wound from the .40 bullet presented a circular shape, with the highest stress concentrated in the inferior edge. A value of 88.83 MPa was the highest stress caused by the wound, which was lower than the stress caused by the .380 and 9 mm bullets. As occurred in the .380 wound, the stress dissipated to the adjacent surface of the occipital bone, which showed low stress values (Fig 5B).

The highest stress in the 9 mm wound was 181.6 MPa, which was located in the superior border of the orifice in the inner bone surface. Part of this energy was dissipated to the occipital bone, which presented low stress values (Fig 5C).

Discussion

Improved head models have been developed to evaluate several parameters of different types of lesions, such as localized brain motion, intracerebral acceleration and intracranial pressure. Real experiences were used to compare and validate the results provided by the models, showing satisfactory behaviors [10, 42-43]. Different parts of the head were tested for impacts on the frontal [13], temporal and parietal [44] regions, as were varying exposure times and load directions in the occipital region [45-48]. Collision tests using physical models and including the occipital region and human neck were also made, and the test results and calculations provided by the Finite Element Model (FEM) had good agreement [49].

The FEM is commonly used for experimental studies in human heads to enhance the understanding of the mechanism(s) of injury via a dynamic analysis [50]. Therefore, injury identification criteria can be established and patterns can be found to indicate the relationships between probable agents and receptors [45]. The mechanical and dynamic impact conditions and formation of fractures were identified using these models in forensic reconstructions, with biological variability in their geometry, thickness, stiffness, number of sutures and skull density [51].

The association between the technical-scientific knowledge set and criminalistics contributes to reconstructing injuries or death caused by projectiles. The victims executed by firearms who have bullets fired into the occipital region have specific morphological features, and understanding the features of these wounds is important for interpreting and determining the shooter distance, bullet velocity, reach, action, direction, angle variations and sometimes the caliber size. Due to specific factors, such as differences in both firearms and projectiles and the features mentioned above, it may be possible to determine how the weapon was held and the position of the victim when it was fired (standing, lying down, kneeling or face down). Police and judicial investigations can be aided by such evidence in criminal cases [26]. In the present study, the skull position was selected based on reported cases in the literature, featuring an execution with the victim looking down and the projectile output pointed toward the occipital bone.

Cases in which the victim was shot in the occipital region with characteristics of an execution have been reported [52-56], where the impact region and general state of the body were depicted but the type of gunshot that caused the injury was not. The aim of this work was to contribute to the interpretation of the findings in similar cases, providing a tool to suggest the type of firearm, distance from which the shot was fired and probable projectile based on the features of the injuries in this region. This will help provide a larger number of elements that can aid in solving crimes.

Calculating the impact of the bullet on the skull allows for a morphometric study of the wound in the bone structure, a described in a study conducted in the glabellar region [13], in which the region of the wound presented an irregular format with a triangular aspect. In contrast, when the wound is in the occipital bone, it is oval or circular. These different features are largely related to the bone morphology and to the bullet's angle of entry. This association between the bone region and angle of entrance is important when a computational simulation is used as a tool for identifying the caliber of the bullet used.

Computational simulations are based on models because of the complexity of real situations. It is therefore impossible to take into account all of the parameters involved in the process, such as the gases produced during the combustion of a propellant charge and the absence of soft tissues that could influence the wound morphology. Future studies including angle and distance variations, other types of munitions, as well as the other skulls are necessary to establish the anatomical variability in the patterns of the wounds caused by firearms in this region.

Conclusion

The simulations enabled the characterization of the injuries after bullet penetration into the occipital bone. In this bone, the three wounds from three different calibers of bullets showed a similar morphology, but there were different morphometric data as well as different levels of stress and types of stress dissipation. These data are important to develop optimal simulation protocols to be applied in forensic traumatology, especially in cases of gunshot wound identification. Moreover, the finite element models allow for a dynamic analysis with sufficient flexibility to support adjustments based on behavioral estimates and the results of experimental trials.

Acknowledgments

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3 CONCLUSÃO

As simulações permitiram a caracterização das lesões após a penetração dos projéteis no osso occipital. Neste osso, as três feridas de três diferentes calibres apresentaram morfologia semelhante, mas apresentaram diferentes dados morfométricos, bem como diferentes dissipação das tensões. Esses dados são importantes para determinar protocolos de simulações e aplicá-las em traumatologia forense, em caso de identificação de ferimentos por arma de fogo. Além disso, os modelos de elementos finitos permitem gerar o análise dinâmico com a flexibilidade suficiente para suportar os ajustes com base em estimativas de comportamento e resultados de ensaios experimentais.

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ANEXOS

ANEXO 1 – Artigo submetido ao periódico: PLOS ONE Journal.

PONE-D-16-06316
Characterization of Gunshot Wounds in the Occipital Bone Region Using Finite Element Dynamic Simulation
PLOS ONE

Dear MS Lopez Quintero,

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ANEXO 2 – Certificado do Comitê de Ética em Pesquisa da Fop-Unicamp.

COMITÊ DE ÉTICA EM PESQUISA
FACULDADE DE ODONTOLOGIA DE PIRACICABA
UNIVERSIDADE ESTADUAL DE CAMPINAS

CERTIFICADO

O Comitê de Ética em Pesquisa da FOP-UNICAMP certifica que o projeto de pesquisa **"Simulação dinâmica de projéteis disparados contra a região occipital do crânio humano - análise de elementos finitos"**, protocolo nº 123/2015, dos pesquisadores Yuli Andrea López Quintero, Alexandre Rodrigues Freire e Ana Cláudia Rossi, satisfaz as exigências do Conselho Nacional de Saúde - Ministério da Saúde para as pesquisas em seres humanos e foi aprovado por este comitê em 19/10/2015.

The Ethics Committee in Research of the Piracicaba Dental School - University of Campinas, certify that the project **"Dynamic simulation of projectiles fired at the occipital region of the human skull - finite element analysis"**, register number 123/2015, of Yuli Andrea López Quintero, Alexandre Rodrigues Freire and Ana Cláudia Rossi, comply with the recommendations of the National Health Council - Ministry of Health of Brazil for research in human subjects and therefore was approved by this committee on Oct 19, 2015.

Fernanda Miori Pascon
Profa. Dra. Fernanda Miori Pascon
Secretária
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Coordenador
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