UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ODONTOLOGIA DE PIRACICABA

SARAH TEIXEIRA COSTA

SIMULAÇÃO DINÂMICA POR ELEMENTOS FINITOS DE FERIMENTOS PRODUZIDOS POR ARMAS DE FOGO NA MANDÍBULA HUMANA.

DYNAMIC SIMULATION BY FINITE ELEMENT ANALYSIS IN INJURIES PRODUCED BY FIREARMS IN THE HUMAN MANDIBLE.

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

Dissertation presented to the Piracicaba Dental School of the University of Campinas in partial fulfillment of the requirements for the degree of Master in Dental Biology in the Forensic Dentistry & Ethics area.

Orientador: Prof. Dr. Felippe Bevilacqua Prado

Coorientador: Prof. Dr. Alexandre Rodrigues Freire

ESTE EXEMPLAR CORRESPONDE À VERSÃO FINAL DA DISSERTAÇÃO DEFENDIDA PELA ALUNA SARAH TEIXEIRA COSTA E ORIENTADA PELO PROF. DR. FELIPPE BEVILACQUA PRADO E COORIENTADA PELO PROF. DR. ALEXANDRE RODRIGUES FREIRE.

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RESUMO

Complicações podem surgir em ferimentos de projéteis no crânio, especialmente na região maxilofacial, quando o projétil ou a arma não são encontrados na cena do crime. A fim de auxiliar nesses casos, este estudo realizou previamente uma revisão sistemática da literatura e estabeleceu um modelo de elementos finitos de uma mandíbula e projéteis totalmente encamisados de calibre .40 Smith & Wesson (S&W), .380, e 9x19 mm Luger. As bases de dados Pubmed, Scopus e Web of Knowledge foram pesquisadas com as palavras chaves finite element gunshot, em busca de variáveis que afetam a precisão dos resultados. Em seguida, um modelo tridimensional de elementos finitos das estruturas ósseas da mandíbula foi estabelecido a partir de dados de tomografia computadorizada. A superfície tridimensional da mandíbula foi exportada no formato estereolitográfico (STL). O modelo tridimensional de CAD 3D da mandíbula foi construído a partir do STL. O modelo da mandíbula, bem como os modelos das munições, foram construídos com uma superfície livre não uniforme (NURBS) por um método de engenharia reversa. Foi descrita a distribuição de tensão von Mises na mandíbula, destacando a existência de áreas potencialmente fracas em algumas estruturas anatômicas, com foco em distâncias curtas (5 e 15 cm). Comparações da morfologia da superfície externa do orifício de entrada foram feitas. Foram selecionados 10 artigos que forneceram detalhes sobre as simulações das referências pesquisadas. Os resultados exibiram diferentes orifícios de entrada e diferentes padrões de tensões de von Mises para cada projétil disparado. A mandíbula foi mais afetada pelo calibre .40 S&W.

Palavras-Chave: Análise de elementos finitos. Mandíbula. Odontologia Legal. Morfologia.

ABSTRACT

Complications may arise in gunshot wounds, especially to the maxillofacial region, when neither projectile nor gun is found at the crime scene. In order to help those cases, this study previously made systematic review and established a finite element model of a human mandible and fully metal-jacketed projectiles .40-caliber Smith & Wesson (S&W), .380-caliber, and 9x19-mm Luger. Data bases Pubmed, Scopus and Web of Knowledge were searched with the keywords finite element gunshot, in order to find variables that affect accuracy results. A 3D finite element model of the human mandible bone structures was established from computed tomography data .The 3D mandible surface was exported in stereolithographic (STL) format. The 3D CAD model of the human mandible was built from the STL. The mandible model and the model of the ammunition were constructed with freeform Non Uniform Rational B-Splines (NURBS) surfaces by a reverse engineering method. It was described the von Mises stress distribution in the human mandible, outlining the existence of potentially weak areas in some anatomical structures, focusing in close range fire distances (5 and 15 cm). Comparisons of entrance aperture morphological external surfaces were made.10 references furnished details about how simulations occurred. The results displayed different entrance apertures and different von Mises stress patterns for each projectile shot. Mandible was most affected by .40-caliber S&W.

Keywords: Finite element analysis. Mandible. Forensic Dentistry. Morphology.

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LISTA DE ABREVIATURAS E SIGLAS

CAD	-	Computer Aided Design
CBC	-	Companhia Brasileira de Cartuchos
Cu	-	Cobre
FEA	-	Finite Element Analysis
GPa	-	Gigapascal
MPa	-	Megapascal
NURBS	-	Non Uniform Rational B-Splines
Pb	-	Chumbo
q	-	Element quality
S&W	-	Smith and Wesson
STL	-	Stereolithographic
SD	-	Standard Deviation
Sb	-	Antimônio
ULP	-	Universidade Louis Pasteur
VMS	-	von Mises stress

SUMÁRIO

1 INTRODUÇÃO

A região maxilofacial é bastante exposta, sendo alvo comum de feridas por arma de fogo, produzidas tanto pela própria vítima, quanto por outros indivíduos (Tang et al., 2012; Zhen et al., 2012). Além disso, como é uma área exposta, possui uma maior chance de ser atingida por projéteis, principalmente na mandíbula. Concomitantemente, a referida área é próxima de outras estruturas anatômicas nobres da cabeça e do pescoço (Chen et al., 2010; Tang et al., 2012).

Ferimentos causados por projéteis de arma de fogo na região da cabeça são objeto de estudo da traumatologia forense por ampliar os conhecimentos clínicos, abrangendo questões relativas ao tratamento. Já no âmbito forense, o objetivo dos estudos tem o propósito de tentar revelar padrões que facilitem o conhecimento sobre distância e direção do disparo, velocidade, arma empregada e tamanho do projétil (Raul et al., 2008).

A análise de elementos finitos consiste em um método matemático, amplamente usado na área de engenharia, ciências e tecnologia. Após 40 anos de desenvolvimento, a análise de elementos finitos tornou-se uma ferramenta analítica efetiva em pesquisas de biomecânica do crânio (Tang et al., 2012). A análise de elementos finitos é favorável para avaliação mecânica do complexo maxilofacial, devido à produção de resultados confiáveis em tempo reduzido e por possuir excelente reprodutibilidade, permitindo um controle das condições de simulação (Tang et al., 2012; Zhen et al., 2012).

Esta análise permite criar estruturas tridimensionais com formas complexas e quantificar, indiretamente, o seu comportamento mecânico em qualquer ponto teórico definido. Como a análise de elementos finitos utiliza as teorias da elasticidade e equilíbrio estático, os efeitos das várias forças externas que atuam sobre um sistema podem ser avaliados como eventos físicos em termos de deformações, e tensões (Raul et al., 2008).

Como crânio é um alvo comum de feridas por arma de fogo, atingindo principalmente a mandíbula com maior frequência, a selecionamos para entender os acontecimentos prévios e durante ao disparo. Para tanto, uma revisão sistemática da literatura foi realizada, a fim de conhecer e estabelecer os padrões atualmente empregados nas análises de elementos finitos que envolvem disparos de arma de fogo e que possuem como alvo a cabeça humana. Após investigar a literatura, notou-se a falta de análise de elementos finitos que avaliaram a distância entre o disparo e o alvo. A determinação dessa condição de disparo é útil para o estabelecimento da real situação ocorrida. Desta forma, verificou-se a necessidade do estudo dinâmico dos ferimentos perfuro contusos, produzidos por projéteis de arma de fogo, na região de mandíbula, utilizando a análise de elementos finitos, para aplicação em futuras pesquisas e em âmbito forense.

O presente estudo teve por objetivo, primeiramente, avaliar a segurança dos padrões utilizados na análise de elementos finitos na região craniofacial. Em seguida, o propósito foi realizar uma análise dinâmica de elementos finitos, simulando a mandíbula como alvo de projéteis de arma de fogo, disparados a diferentes distâncias. Em posse dos resultados, o intento seguinte foi correlacionar os padrões das lesões produzidas e determinar os locais de maior tensão na mandíbula, em ponto previamente estabelecidos.

2 ARTIGOS

2.1 SYSTEMATIC REVIEW OF FINITE ELEMENT ANALYSIS: USE IN CRANIOFACIAL GUNSHOT WOUNDS.

Artigo submetido ao periódico: Australian Journal of Forensic Sciences (Anexo 1).

Autoria: Sarah Teixeira Costa; Alexandre Rodrigues Freire; Ana Cláudia Rossi; Felippe Bevilacqua Prado.

Abstract

The study of wound ballistics should include biomechanical science for better results in diagnosis, treatments and prognosis. Finite Element Analysis can provide interesting tools when human head injuries need to be evaluated. The present study is the first step in systematic study the use of finite element analysis in craniofacial gunshot wound. The study aimed to systematically review: 1) the use of Finite Element Analysis on heads injuries, especially gunshot wounds, 2) safety of using standard patterns of Finite Element Analysis and 3) analyze and discuss advantages and deficiencies of finite element models. Electronic research databases, Pubmed, Scopus and Web of Knowledge, were searched using restricted key words: finite element gunshot. Studies were included if they: reported finite element analysis in heads, simulating gunshot injuries. Excluded studies were those which did not clearly describe their methods and results, had significant discrepancies, were not published in the English language or were not published yet. There were 30 references identified by the bibliographic search strategy. Fourteen articles were eligible for inclusion and were fully critically appraised. The collected data was able to furnish details that the simulations occurred, as well as, some variables that may affect the predictive accuracy of the simulation.

Key words: finite element analysis; gunshot wounds; craniofacial.

Introduction

Literature on the management of gunshot wounds began to appear soon after firearms joined field artillery already in the battlefield [1]. Much of what is known about how penetrating injuries damage the brain and how this damage is best treated, was learned from studying the many thousands of soldiers who received head injuries during World War II, Korea, and Vietnam [2].

Gunshot wounds to the head are the most lethal type of injury in civilian head trauma [3]. This situation has encouraged scientists and physicians to define the mechanisms and basic principles of wound ballistics in the head and neck, for clinical, forensic, and military purposes. Recently, the technological development has facilitated researchers to focus on the biomechanical mechanisms of wound ballistics both experimentally and computationally. However, due to the difficulty of reproducing the complex anatomical structures, the dynamic interactions between projectiles and tissues have not been extensively researched, except for a few reports on clinical data or some experimental studies. As an effective mathematical method for solving complex mechanical problems with complicated geometries, the finite element method is widely utilized in medical research for the study of biomechanical mechanisms in head [4].

With the advanced of engineering modeling techniques, it is possible to quantify injury biomechanics using finite element models. Such computer models can offer complimentary and unique perspectives on internal responses of the skull and brain. An increased understanding of the wounding processes may assist in better treatment [3]. Friedenberg was the first to employ the finite element method for medical research in 1969 [5].

The present study proposes, systematically, identify and appraise international evidence for the utilization of finite element analysis (FEA) in craniofacial gunshot wounds. The review also deals with the safety of using standard patterns of FEA to determine the injury mechanism as well as discussions about advantages and deficiencies of each finite element model found.

Materials and Methods

Eligibility criteria

Studies were included if they: reported finite element analysis in heads, simulating gunshot injuries. Any study that described a theoretical or practical finite element analysis or model was also eligible for inclusion in this review.

Excluded studies were those which did not clearly describe their methods and results, had significant discrepancies, were not published in the English language or were not published yet.

Information sources

A systematic method of literature searching and selection was employed in the preparation of this review. Three electronic research databases, Pubmed, Scopus and Web of knowledge, were rummaged using the following restricted keywords: finite element gunshot. The quest was restricted by English language, but it was not restricted by publication date.

Database searches were performed from inception to February 2014, on May 2014, and then on October 2014. Publications identified were considered between July 1988 and October 2014 inclusive. The oldest publication was Wind *et al.*, 1988.

An initial 'screening search' was conducted on February 2014 considering FEA generally. On May and October, seek was restricted to FEA on heads and simulating gunshots.

Some articles were not fully available on data sources. Correspondent authors needed to be contacted in order to achieve these references.

Study selection

Studies were selected for appraisal using a two-stage process. Initially, the titles and abstracts identified from the search strategy were scanned and excluded as appropriate. The full-text articles were retrieved for the remaining studies and these were appraised if they fulfilled the study selection criteria outlined previously.

The studies were initially selected by examining the abstracts of these articles. Therefore, it is possible that some studies were inappropriately excluded prior to examination of the full-text article. To minimize this possibility, where detail was lacking or ambiguous, papers were retrieved as full text. In addition, cross-checking of references of retrieved papers, including those of a large number of papers retrieved as background, was employed to identify additional potentially eligible articles.

Data collection process

Retrieved studies were assessed for relevance by a single reviewer and decisions on final inclusion checked by a second reviewer; disagreements were resolved by discussion with a third reviewer.

Data from included trials were extracted by a single reviewer into data extraction tables and then checked independently by a second reviewer.

Whenever a finite element analysis or model were presented in more than one publication, data were extracted initially from the original source and complemented, if necessary, with information presented on subsequent publications that reported on its use.

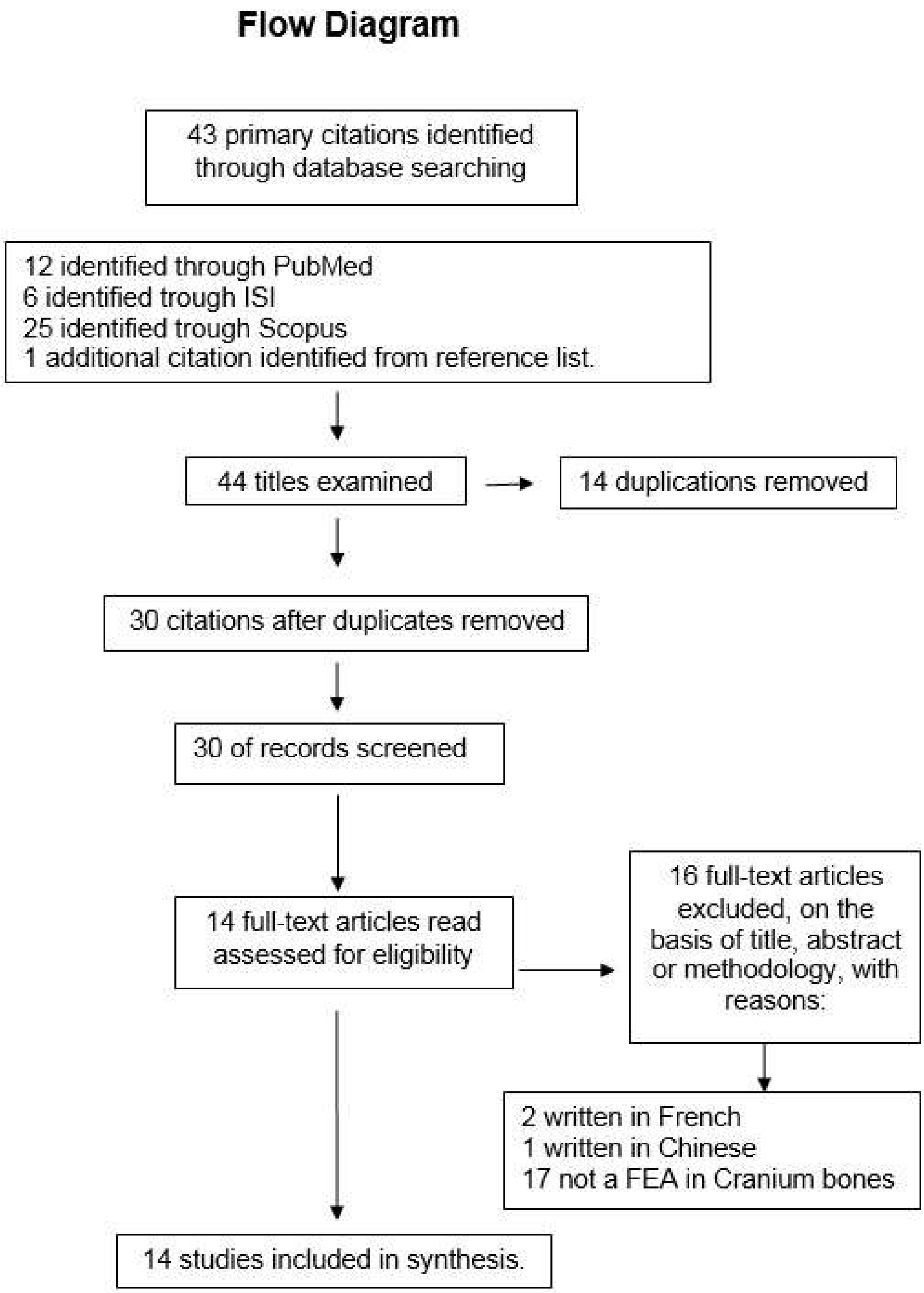
Data items

Information extracted from each article included: boundary conditions, element type, FEA models and simulating softwares. Specifications of the projectiles were also taken, as calibers, bullet mass, initial velocity, impact velocity, shooting distance, incidence angle and incidence local.

Results

There were 30 references identified by the bibliographic search strategy. Sixteen of these 30 articles did not fulfill inclusion criteria and were excluded. Fourteen articles were eligible for inclusion, listed in, and were fully critically appraised (Figure 1)

Figura 1- Flow Diagram



Searching criteria was not restricted by publication date. Article search was completed on October 2014. The majority of studies were experimental studies, except for an editor letter [6] and a review article [7]. Articles found are listed in Table 1, related to databases and reasons for exclusion. One article [29] is not listed on tables according to databases because was found reading a reference list. Although it is written in French, the article relates relevant information and could not fail to be consulted.

Table 1 - Distribution of articles identified by descriptor finite element gunshot related to databases.

	Selected	*	Excluded	*	Reasons for exclusion
Pubmed	Matoso *et al.,* 2014	8			
	Karimi *et al.*, 2014	9	Shen *et al.,* 2010	4	Not a FEA on cranium bones
	Stefanopoulos, 2013	6	Takahashi *et al.,* 2010	15	Not a FEA on cranium bones
	Tang *et al.,* 2012	10	Roberts *et al.,* 2007	16	Not a FEA on cranium bones
	Chen *et al.,* 2010	4	Bozhus *et al.,*2005	17	Not a FEA on cranium bones
	Raul *et al.,* 2007	11	Wind *et al.*, 1988	18	Not a FEA on cranium bones
	Pintar *et al.,* 2001	1			
ISI	Tang *et al.,* 2012	10			
	Raul *et al.,* 2007	11			
	Raul *et al.,* 2008	7	Ionescu, 2006	19	Not a FEA on cranium bones
	Mota *et al.*, 2003	2			
	Zhang *et al.,* 2003	3			
Scopus	Pekedis,Yildiz, 2014	12	Tang *et al.*, 2014	20	Not a FEA on cranium bones
	Karimi *et al.*, 2014	9	Salimi *et al.*, 2014	21	Not a FEA on cranium bones
	Stefanopoulos, 2013	6	Tang *et al.* ,2011	22	Written in Chinese
	Tang *et al.,*2012	10	Shen *et al.,* 2010	4	Not a FEA on cranium bones
	Zhen *et al.,* 2012	5	Takahashi *et al.,* 2010	15	Not a FEA on cranium bones
	Chen *et al.,* 2010,	4	Wang *et al.,* 2009	3	Not a FEA on cranium bones
	Raul *et al.,* 2007	11	Merkle *et al.* ,2008	24	Not a FEA on cranium bones
	Raul *et al.,* 2008	7	Roberts *et al.* ,2007	6	Not a FEA on cranium bones
	Zhang *et al.,* 2003	3	Roberts *et al.,* 2007	25	Not a FEA on cranium bones
	Pintar *et al.,* 2001	1	Bozhus *et al.,* 2005	18	Not a FEA on cranium bones
	Pintar *et al.,* 2000	13	Xiao *et al.,* 2005	26	Not a FEA on cranium bones
			Raul *et al.,* 2002	27	Written in French
			Raul *et al.,* 2004	28	Written in French
			Wind *et al.*, 1988	18	Not a FEA on cranium bones

A systematic review attempts to reduce the influence of bias by undertaking an extensive search for all published studies. In finite element models, some assumptions greatly affect the predictive accuracy, such as boundary conditions, element types, model and model validation. These variables affect the predictive accuracy of the simulation and should be taken into account in the evaluation of the results and conclusions. Table 2 demonstrates some variables which may affect the simulation and their way of application according to authors. This table considers only experimental studies.

Table 2 - Elements which affect FEA.

(continua).

*	References	Boundary conditions	Element type	FEA models	Softwares
9	Karimi *et al*., 2014	The nodes of the condylar region were constrained at the x, y, and z directions	Hexahedral elements.	A 3D finite element model of the human mandible.	LS-DYNA
8	Matoso *et al.,* 2014	Displacement restrictions were applied along the three axes (x, y, z) in the lower plane section.	Tetrahedral elements.	A three dimensional skull finite element model.	AUTODYN
12	Pekedis & Yildiz, 2014	For the mandible impact, the condylar region was fixed in three directions. For frontal impact, the projectile was directed to the forehead just superior to the orbital ridges. For the maxillary impact, the projectile was aimed at the zygomatical bone.	Orthotropic materials properties.	Skull was modeled by smoothed particle hydrodynamics.	Not mentioned.
10	Tang *et al.,* 2012	The elements of the condylar region were fixed in the X, Y and Z directions.	Homogenous and isotropic. Hexahedral elements.	Established using a method similar to that used for the previously developed 3D pig mandible.	LS-DYNA
5	Zhen *et al.,* 2012	The elements of the condylar region were fixed in the X, Y and Z directions.	Homogenous and isotropic. Hexahedral elements.	Established using a method similar to that used for the previously developed 3D pig mandible.	LS-DYNA
4	Chen *et al.,* 2010	The elements of the condylar region were fixed in the X, Y and Z directions.	Homogenous and isotropic. Hexahedral elements.	A finite element model of the pig mandible. Established to validate other studies.	LS-DYNA

Table 2 – Elements which affect FEA
(conclusão).

*	References	Boundary conditions	Element type	FEA models	Softwares
11	Raul *et al.*, 2007	Not mentioned	Homogenous and isotropic	University Louis Pasteur (ULP) model	Not mentioned
2	Mota *et al.*, 2003	Not mentioned.	Homogenous and isotropic Tetrahedral elements.	A model was built with the discretized equations of motion integrated in time by Newmark's explicit time stepping algorithm.	Not mentioned.
3	Zhang *et al.*, 2003	All external nodes were unconstrained in all degrees of freedom.	Not mentioned.	A three dimensional skull-brain finite element model.	LS-DYNA
1	Pintar *et al.*, 2001	The model was constrained at the inferior surface of the cranial bone representing the approximate area of foramen magnum.	Isotropic Eight-noded brick elements.	A three dimensional finite element model of skull-brain. The geometrical shape of the head was assumed as a sphere.	LS-DYNA
13	Pintar *et al.*, 2000	The model was constrained at the inferior surface of the cranial bone representing the approximate area of foramen magnum.	IsoparametricEight-noded brick elements.	A three dimensional finite element model of skull-brain. The geometrical shape of the head was assumed as a sphere.	LS-DYNA

In order to correctly provide specifications about simulation conditions follows some projectiles particularities used by references selected in Table 3. Those data are able to furnish details that the simulations occurred, allowing reproductions and comparisons.

Table 3 - Specifications of the projectiles.

*	References	Calibers	Bullet mass	Initial Velocity	Impact Velocity
9	Karimi *et al*., 2014	6,3 mm	1,03 g	Not mentioned	734 m/s
8	Matoso *et al.,* 2014	9 mm. .380 .40	7,45 g 6,16 g 11,66 g	343 m/s 288 m/s 300 m/s	Not mentioned
12	Pekedis & Yildiz, 2014	37 mm	20 g	800 m/s	Not mentioned
10	Tang *et al.,* 2012	7,62 mm 6,3 mm	7,92 g 1,03 g	Not mentioned	400m/s; 734m/s and 1109.2m/s
5	Zhen *et al.,* 2012	7,62mm 6,3 mm	7,92 g 1,03 g	Not mentioned	400m/s; 734m/s and 1109.2 m/s
4	Chen *et al.,* 2010	7,62 mm	7,92 g	Not mentioned	732,6 m/s
11	Raul *et al.,* 2007	.22	2,5 g	310 m/s	Not mentioned
3	Zhang *et al.,* 2003	Flat head and pinpointed head	9 g	Not mentioned	300 m/s
2	Mota *et al.,* 2003	0.22, 0.25, 0.32, 0.38	Not mentioned	600 m/s and 1000 m/s	Not mentioned
1	Pintar *et al.,* 2001	One with flat-face geometry and the other with pointed geometry	Not mentioned	700 m/s	Not mentioned
13	Pintar *et al.,* 2000	One with flat-face geometry and the other with pointed geometry	Not mentioned	700 m/s	Not mentioned

Shooting conditions, as well as projectiles particularities, are relevant in future comparisons and are listed in Table 4.

Table 4 - Shooting conditions.

(continua)

*	References	Distance	Incidence angle	Incidence Local
9	Karimi *et al*., 2014	Not mentioned	90^o and 70^0	Human mandible
8	Matoso *et al.,* 2014	10 cm	90^o	Frontal, glabella
12	Pekedis & Yildiz, 2014	Not mentioned	Not mentioned	Forehead, zygoma and mandible
10	Tang *et al.,* 2012	Not mentioned	90^0; $67{,}5^0$ e 45^0	Human mandible

Table 4 – Shooting conditions.
(conclusão)

*	References	Distance	Incidence angle	Incidence Local
5	Zhen *et al.,* 2012,	Not mentioned	Vertical to the lateral plane of mandibular angle	Human mandible
4	Chen *et al.,* 2010	6m	Vertical to the lateral plane of mandibular angle	Angle of pig mandible
11	Raul *et al.,* 2007	Not mentioned	Not mentioned	One bullet fired the frontal and ethmoid bones. The other bullet penetrated the right temporal bone.
3	Zhang *et al.,* 2003	Not mentioned	Not mentioned	Head
2	Mota *et al.,* 2003	Not mentioned	Not mentioned	Parietal
1	Pintar *et al.,* 2001	Not mentioned	Not mentioned	Temporal
13	Pintar *et al.,* 2000	Not mentioned	Not mentioned	Temporal

This study has used a structured approach to review the literature included for appraisal. However, there were some inherent limitations with this approach. Namely, systematic reviews are limited by the quality of the studies included in the review as well as the review's methodology.

The results of a systematic review can therefore be susceptible to publication bias.

The current systematic review excluded non-English publications, so a possible language bias appears.

Furthermore, FEA is a brand new approach to topic and there is not a lot of article about this subject. The number of included trials (10 studies) was too small to conduct any sufficient additional analysis of publication bias.

Discussion

There is a consensus among most authors that FEA is able to supply tools for forensics matters, especially when head injury mechanisms need to be evaluated. FEA may help to evaluate different scenarios giving the possibility to exclude some them [7,9].

Finite element method offers many features, such as, represent anatomical structures and biomechanical properties similar to those of the human body. Besides, it is direct and dynamic, so as to easily observe and analyze stress patterns in each region to reproduce the whole injury process. Model also reproduces with easy storage analyzes results [5].

FEA offers many advantages. First, it is possible to adjust the entry orientation and impact velocity of projectiles. When material parameters and geometrical shape of the projectile are available, the penetration of different projectiles can also be simulated. Second, there is the possibility to study any location in the model to dynamically monitor the stress pattern. Finite element flexibility enables to quickly simulate injuries to any region induced by gunshots with any type of projectile and from any entry angle and velocity under real conditions. Third, the established finite model can be used repeatedly. Regardless of any changes in the loading conditions, the initial state of the chose study subject remains constant, which ensures the comparability of the results of different research models [5,10].

Meanwhile, there are some shortcomings on finite element model due to medical ethics limitations, which restricts cadavers models used as experimental gunshot wound data. Thus, the model cannot be validated [10]. Smoothed particle hydrodynamics models are unable to be directly validated with a physical test [12]. However, some referred models were validated. Finite Element model used by some authors [5,10] were validated as the following: seven pig mandibles, which were cut in half through the midline, with removal of adhering muscles and periosteum. Each segment was shot at a firing distance of 6m by a 7, 62 mm projectile at an approximate right angle to the lateral part of the mandibular angle. For each shot, the impact velocity and the residual velocity of the projectile were measured by a velocimeter system [4]. The head University Louis Pasteur (ULP) model validation consisted in three cadaver head impact simulation [11,29]. It is important to highlight that ULP model validation was not made with projectiles, but with pendulums. Physical gelatin model was used to delineate the penetrating wound profiles for different projectile types, considering as a validation data for a finite element model [1,13].

Acknowledged factors that may also influence the outcomes are the absence of soft tissues on finite element models. This problem frequently happens, as it is possible to find in many studies [2,4,5,8,10,12]. Interaction of soft tissues could play a dissipative role, absorbing some of the energy from the impact, and thereby reducing the wound diameter [2]. Certain discrepancies between results and real conditions are undoubtedly inherent to the methodology based on previous finite element model of pig mandible, containing only hard tissue. For example, in a previous study, significantly higher amounts of energy transfer, exceeding 1000 J, were reported for military type rifle projectile penetrating real pig heads through the posterior mandible, which can only be explained by projectile tumbling promoted by bone contact and soft tissue intervention. Cavitation changes within bone marrow have not been addressed, although such changes can probably be deduced from some stress patterns [6,10]. However, other references [1,3,7,11,13] took into account not just hard tissues. In most of these studies, side effects on brain were considered.

Researches in mandibular bones did not regarded teeth. The teeth were not a primary concern and were assumed be part of the mandible with the same mechanical properties as the cortical bone [4,5,9,10]. This may disclose a weakness in their model.

Boundary conditions vary. Some references constrained at the inferior surface of the cranial bone representing the approximate area of foramen magnum [1,13] . Another way found was the elements of the condylar region of the finite element model fixed in the X, Y and Z directions [4,5,8,9,10,12]. Model boundary less used was all external nodes unconstrained in all degrees of freedom [3]. Moreover, the lack of detailed information regarding model boundary is present in some studies [2,7,11].

Concerning the elements types, many considered the elements hexahedral [4,5,9,10]. Only one reference used tetrahedral elements [8]. It was regarded to be homogenous and isotropic. Elements types were also named as eight-noded brick [1,13]. The continuity of elements is highly essential for FE analysis. Only continuous elements can successfully transmit stress in structures. Using 3D hexahedral elements can reduce the quantity of elements, improve solution precision, and decrease computation time. To discretize structures with continuous elements, the limitation of mapped mesh is higher than that of free mesh types. Hence, models with complex geometry are typically difficult to design and should be pre-planned using a mapped mesh type before discretization. The difference in limitations between free mesh models that use 2D triangle or 3D tetrahedral elements is relatively fewer, although free mesh increases the element quantity and computation time [30].

The numerical simulations were performed in the software LS-DYNA in most studies, but some authors, did not mentioned the software [11,12].

The speed incidence of the projectile in human bones ranged between 300m/s and 1109.2 m/s, being the maximum velocity used in the studies of Tang et al

[10] and Zhen et al [5], and the minimum resorted at Zhang et al [3]. Related to angles, the vast majority of researches focused the projectile entry angle in 90^0, perpendicular to the sagittal mandibular plane. However, just two references made the penetrating wounds in different angles, 45^0, 67.5^0, 70^0 and 90^0 [9,10]. FEA of projectile caliber 7.62 mm was the most meshed ones, with a mass of 7,92g. Trauma location varies with the study. The most affect bone were mandible [3,5,9,10,12] followed by temporal [1,13].

Some patterns are not yet well established. Among most authors, there is an absence of detailed information concerning teeth presence, soft tissue, boundary conditions, validation way and software used. Since these topics were not equal in all studies analyzed, comparisons should be taken with caution, taking into account every difference between researches.

According to the literature, FEA appear to be a promising tool for assessing the consequence of a given gunshot wound scenario and for future ballistic studies. Good comprehension of this technique and evolution of computer capability will help developing its use in forensic routine practice. FEA advantages found were: good representation of anatomical structures, easy storage and easy reproduction. The only deficiency detected were ethics limitations in validating the model. However, patterns are not yet well fixed in literature. There are no consensus among authors regarding the better model boundary, software used, model validation and element type.

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2.2 COMPUTATIONAL APPROACH TO IDENTIFY DIFFERENT INJURIES BY FIREARMS.

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ABSTRACT

This study established a finite element model from a human mandible and full metal-jacket projectiles .40-caliber S&W, .380-caliber, and 9x19-mm Luger. A 3D finite element model of the human mandible bone was established from computed tomography data. The 3D mandible surface was exported in stereolithographic (STL) format. A 3D CAD model of the human mandible was built. The mandible and ammunition models were constructed with freeform Non Uniform Rational B-Splines (NURBS) surfaces using a reverse engineering method. The von Mises stress distribution outlined the existence of potentially weak areas in anatomical structures in the human mandible at close firing range distances (5 and 15 cm). The entrance apertures on morphological external surfaces were compared. There were different entrance apertures and von Mises stress patterns for each projectile shot. The mandible was most affected by .40-caliber S&W. Finite element models are useful for forensic cases that involve gunshots to the mandible.

Key words: forensic science, forensic dentistry, mandible, finite element analysis, gunshot wounds, projectiles.

Firearm injuries were responsible for the majority of deaths in Brazilians (1). The growing trend in mortality from projectiles in the male Brazilian population is evident. The mortality rate was 39 per 100,000 habitants in 2000 (2). The maxillofacial region is one of the most commonly targeted areas by firearm projectiles. This region is frequently targeted by projectiles because it is an exposed area (3,4,5). The mandible suffers the highest incidence of injuries caused by firearms projectiles, and the body region is the most affected (6). The mandible is the only mobile bone of the face, and it is more prone to injuries than the other bones of the middle third of the face, which have greater bone support (1).

Analyses of trauma to the mandibular bone area are important in forensic research. The understanding of gunshot wound characteristics is an important matter for interpreting the distance, velocity, direction and, occasionally, caliber size. The evaluation of gunshot wounds can help reconstruct the events surrounding a death (7). Assays of gunshot wounds features may deliberately provide an entire overview of the events that occurred at the crime scene. Some important aspects related to the shooter may be unveiled, such as target distance, projectile velocity, projectile direction and caliber size (7).

The maxillofacial region is an exposed part of the body, and it is a common location of gunshot wounds (4). Projectiles have obvious evidentiary value, but projectiles of handguns are not frequently recovered during an autopsy. The absence of triggered projectiles may lead to inconclusive results during the investigation and solving of criminal cases. Unfortunately, this situation is very common, and it must be overcome. Gunshot wounds may disclose aspects that are related to the events surrounding the shooting (8).

Uncertainties in such cases include the caliber, firing direction and shooter. The first step in resolving these problems is to establish whether the wound is an entrance or exit wound. Bevel distinguishes entrance wounds from exit wounds, especially in dry skulls. Entrance wounds are round or ovoid in shape, which highlights the beveling of the wound’s inner table (7).

Firing range is the critical issue to uncloak in gunshot fatality investigations. The most common method of determining distance is the use of gunshot residue analysis. However, these products of firearm discharge may not be available, and most experimental studies are based on animal models (9).

We developed a finite element model of a human mandible and .40-caliber S&W, .380-caliber and 9x19-mm Luger projectiles to circumvent these and other limitations related to ethics. This study simulated 5- and 15-cm firing distances at a human mandible to investigate the external morphology of entrance wounds based on fire range.

Methods

The Committee for Ethics of Research of the State University of Campinas (Protocol number CEP-FOP-UNICAMP-028/2013) approved this research.

We simulated the following shooting conditions: a pistol loaded with .40-caliber S&W, .380-caliber, and 9x19-mm Luger projectiles pointed perpendicularly to the mandibular body toward the second molar below the oblique line at 5- and 15-cm firing distances.

1. Sample and images acquisition

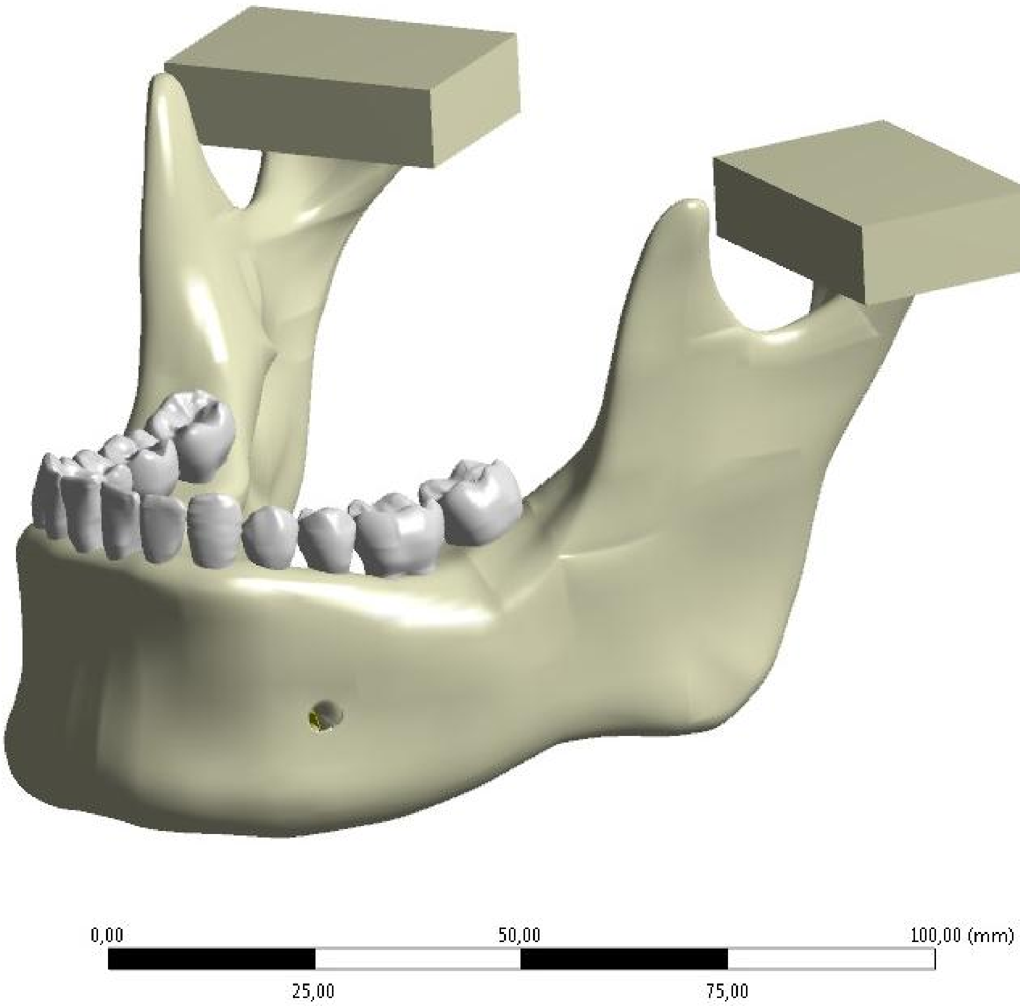
A dry human mandible from the Laboratory of Anatomy of Piracicaba Dental School, State University of Campinas, Brazil, was randomly chosen based on a previous study from our research laboratory (10). The mandible was from an unidentified man. It was intact with no macroscopically visible bone pathology, and all anatomical structures were preserved.

Bone surface images of the human mandible were acquired using computed tomography scans (GE HiSpeed NX/i CT scanner, General Electric, Denver, CO, USA) at a 0.25-mm slice thickness. The anatomical structures were segmented, and a 3D image of the mandible surface was obtained and exported in a stereolithographic (STL) format using the Materialise MIMICS v17 software (Materialise, Leuven, Belgium).

2. CAD geometry construction

The 3D CAD geometry of the human mandible was constructed from the STL, which included teeth and bone structures (Figure 1). This mandible geometry and the model of the ammunition (.40-caliber S&W, .380-caliber and 9x19-mm Luger projectiles) were constructed with freeform Non-Uniform Rational B-Spline (NURBS) surfaces using a reverse engineering method (6) in the 3D software Rhinoceros 5.0 (McNeel & Associates, Seattle, WA, USA).

Figure 1 - 3D CAD geometry of the human mandible.



Projectiles of the .40-caliber S&W, .380-caliber and 9x19 mm Luger were chosen based on their availability in Brazil (10). These projectiles include full metal jackets. The following people are authorized to use these projectiles:

- .380-caliber: for general use, and ordinary people are allowed use it.

- .40-caliber S&W: exhibits great penetration of barricaded targets, and state military police officers and civil police officers use it.

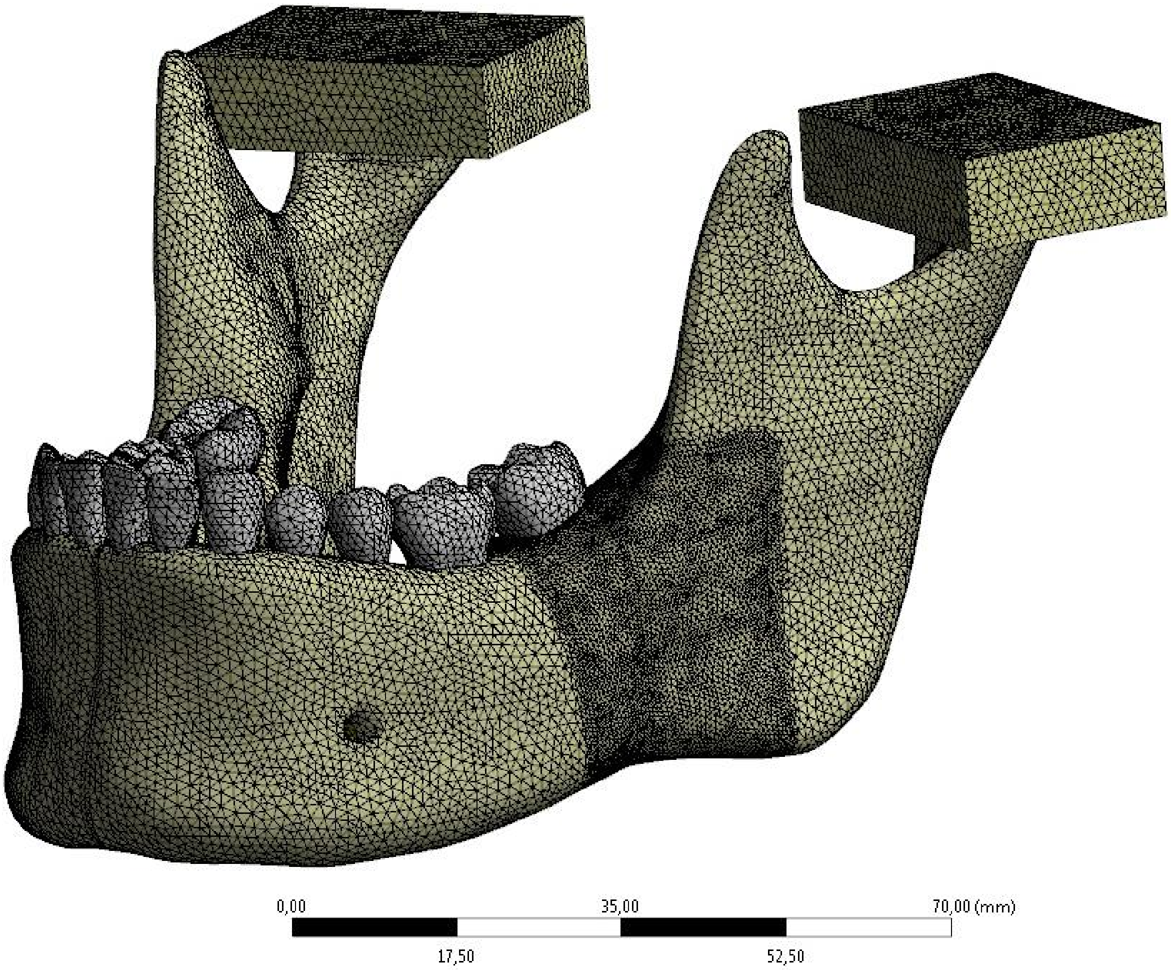
- 9x19 mm Luger: exhibits the greatest penetration, and Brazilian military forces and federal officers use it in any type of semi- or fully automatic weapon.

All constructions were performed according to a previous study (11).

3. Finite element models construction

Geometries were imported into ANSYS v.14 software (ANSYS, Inc., USA) for mesh generation with tetrahedral elements. The final finite element model of the mandible (Figure 2) and .40-caliber S&W was meshed with 758,363 elements and 163,633 nodes. The final finite element model of the mandible and .380-caliber was meshed with 743,860 elements and 160,597 nodes, and the mandible and 9x19 mm Luger was meshed with 743,570 elements and 160,386 nodes.

Figure 2 - The finite element mesh after discretization showing the tetrahedral elements. On the left side, the impact area presented a refined mesh (ANSYS v.14 software - ANSYS, Inc., USA).



Notably, the target zone was refined, i.e., the element size was reduced, to obtain more accuracy (Figure 2). Element quality (q) evaluation using mesh metrics in ANSYS software revealed a q = 0.81 (SD = ± 0.10), in which q=1 is the best possible score.

4. Analysis configuration

The simulations were configured to simulate a gunshot against the mandible model. The projectiles were fired 5 and 15 cm from the lateral surface of mandibular body (9,11,12).

Figure 1 shows the anatomical structures of the mandible geometry: cortical and cancellous bone, teeth and a block, which was subtracted from condyles to represent the mandibular fossa. Blocks were built in both sides, above the mandibular condyle. The mandibular fossa was considered to possess cortical bones properties.

The stiffness properties of bone structures were based on a previous study (13). The analysis of stress in this study was considered for comparisons because of the morphological characteristics of the aperture caused by projectile penetration in the mandible. The mechanical properties of each material in the projectile were selected based on the ANSYS database. The material failure properties of the bone structure were obtained from the database of MatWeb, LLC (14). Table 1 shows the mechanical properties of the finite element models (mandible and .40-caliber S&W, .380-caliber and 9x19 mm Luger).

Table 1 - Properties of the materials used in the finite element models.

Properties	Human Bone	. 380-caliber; .40 -caliber S&W; 9X19 mm Luger	
		Jacket Cu	Core Pb (99%) / Sb (1%)
Young's modulus (GPa)	14 [a]	115	14
Poisson's ratio	0,3 [a]	0,3	0.38
Shear modulus (GPa)	5.3846**	46	8.6
Bulk modulus (GPa)	11.667**	129	-
Density (Kg/m^3)	1850**	8960	11340
Specific heat (J/Kg.uC)	440**	383	124
Tensile Stress failure (GPa)	0.133**	-	-
Shear Stress failure(GPa)	0.067**	-	-

The solver Ansys AUTODYN v14 (Ansys, Inc., USA) was used to perform an explicit dynamic analysis, following the failure criteria according to our previous study (10). The material behavior during the projectile impact and penetration was based on the material failure properties according to the software configuration. The program calculated this process by combining the failure properties, the stress limits on the geometry and the interaction between the models (10).

The coordinate system was left-handed orthogonal with the x-axis pointing from left to right in the transverse plane, the y-axis pointing from caudal to cranial in the vertical plane and the z-axis pointing from mesial to distal in the sagittal plane (15).

The nodes of the condylar region were constrained at the x, y and z directions. For boundary conditions (2, 10, 16, 17), the loading conditions were set in accordance with dynamic explicit analysis, which involved the initial speed and the effect of gravity.

5. Projectiles specifications

Table 2 shows the projectile specifications of velocity conditions, mass, kinetic energy and shape. These specifications were selected according to data provided by a Brazilian manufacturer of weapons and ammunition (Companhia Brasileira de Cartuchos, CBC, Ribeirão Pires, Brazil). The Ansys software was used for the simulation that provided impact velocity and residual velocity.

Table 2 - Muzzle velocity, mass, energy and shape of each projectile in the computational simulation.

Projectile	Shape	Muzzle Velocity (m/s)*	Mass (g)	Energy (J)
.40 S&W	Flat point	300	11.66	524
.380 AUTO	Round nose	288	6.16	256
9x19 mm Luger	Round nose	343	7.45	440

6. Numerical simulation

All data were processed by the solver using an Intel Core i7-3770 3.40 GHz processor, 32 GB Random Access Memory and video card NVIDIA Quadro 4000 (1 GB memory) to perform the analysis.

The region of the mandibular body at the second molar level below the oblique line was chosen to receive the shot in simulation. Anatomical structures such as skin, masseter muscle, and periosteum were not reproduced because these structures do not substantially influence the aim of this study (4). The penetrating simulation was unilateral due to the absence of soft tissues, and only the left part of the bone was analyzed to minimize bias.

7. Shooting conditions

Projectile trajectories were considered parallel to the ground when directed to a mandible (Frankfurt horizontal plane parallel to x-axis) and perpendicular to the sagittal plane of the mandible (a peak to the y-axis). Two simulations for each projectile were performed: 1) Shot was fired at range of 5 cm; and 2) Shot was fired at range of 15 cm (9, 11, 12). These distances correspond to the virtual space between the handgun barrel of the caliber and the mandible portion of the 3D-FE model. The effects caused by air resistance, yaw, precession and nutation were not considered because of the very short-range shooting (10). Gravity was specified in our simulation.

8. Analyses of results

The external morphology of entrance holes in the mandible of the 3D-FE model, wound characteristics (e.g., shape and diameter), energy loss and equivalent von Mises stress (VMS) distributed around the ballistic impact area were analyzed. The VMS on the symphysis region, retromolar region, condylar neck region, mandibular angle, mandibular notch and mandibular foramen region were analyzed to compare the results. These areas were chosen because the middle of the mandibular symphysis, mental foramen region, mandibular angle and the neck of the condyle are potentially weak areas (18, 19).

VMS distribution was analyzed according to the scale for stress, which allows for evaluations of sites of higher and lower intensity (in Megapascal – MPa).

Energy loss from the projectile was determined. We assumed that changes in the mass of the projectile were negligible because there was no projectile fragmentation. The kinetic energy of the projectile pre- and post-collision and the energy transfer were calculated to investigate the degree of damage (4, 10, 11). Therefore, the energy loss was calculated to investigate the damage efficiency that was produced when the projectile penetrated the human mandible.

Results

1. Wound Characteristics

The wound shape produced by a .40-caliber S&W fired at a 5-cm range presented an oval aspect with a maximum diameter of 16.50 mm. The external entrance on the lateral face of the mandible presented a surface area that was larger than the internal entrance. The same pattern was observed at the medial face of the mandible. Therefore, there was greater cortical bone destruction, which suggests bevel formation in both faces. There were two fracture lines at the gunshot entrance wound that started from its inferior surface, at the lateral and medial surfaces, and headed towards the mandible basis. These fracture lines were directed in the same direction, but they were not connected.

The wound shape produced by the .380-caliber fired at a 5-cm range also presented an oval aspect with a maximum diameter of 15 mm. Cortical bone destruction was large at both faces of the mandible, similar to the .40-caliber S&W simulation.

The 9x19 mm Luger fired at a 5-cm range created a round gap of 16.25 mm at its larger diameter after mandible surface penetration.

All of the wounds produced by projectiles fired at 15 cm were predominantly rounded with an external bevel. The major bevel was produced by the .380-caliber. Fractures were present in wounds made by the .40-caliber S&W and the .380-caliber only. Both fractures were directed to the mandibular basis. Maximum diameters created by the 9x19 mm Luger, .380-caliber and .40-caliber S&W were 13.32 mm, 13.75 mm and 15.00 mm, respectively.

2. von Mises stress

The maximum VMS values for the .40-caliber S&W, .380-caliber and 9x19 mm Luger hitting the mandible at 5 cm were 50,837 MPa, 38.4 MPa and 33.19 MPa, respectively. The maximum VMS values of projectiles fired at 15 cm were 33.19 MPa for the .40-caliber S&W, 24.288 MPa for the .380-caliber and 13.109 MPa for the 9x19 mm Luger.

The .40-caliber produced the highest VMS values in the mandibular basis near the entrance hole when fired at 5 cm. Tables 3 and 4 show the VMS values.

Table 3 - von Mises stress for each area in MPa, from shots fired at 5 cm.

Mandible Locations	**.40 S&W-caliber**	**.380-caliber**	**9x19 mm Luger**
Symphysis region	25.41	9.6	3.319-6.637
Retromolar regions	0-25.41	0-9.6	9.956-29.87
Condylar neck region	0-25.41	9.6-28.8	6.637
Mandibular angle	0-25.41	0-9.6	0-3.319
Mandibular notch	30.50	9.6-28.8	3.319-19.91
Mental foramen region	25.41-30.50	0-28.8	9.956

Table 4 - von Mises stress for each area in MPa, from shots fired at 15 cm.

Mandible Locations	**.40 S&W-caliber**	**.380-caliber**	**9x19 mm Luger**
Symphysis region	14.457-33.191	6.2243-11.981	0
Retromolar regions	0-7.9905	0-18.863	0-11.98
Condylar neck region	33.191-51.18	6.2243-24.288	0-6.803
Mandibular angle	14.457-33.191	6.2243-24.288	0-13.109
Mandibular notch	0-7.9905	6.2243-24.288	0-13.109
Mental foramen region	14.457-33.191	0-24.288	0-13.109

Figure 3 and 4 show the stress values at selected areas when the projectiles penetrated through the mandible at two different distances. This image shows the possibility of comparing stress patterns for distinct projectiles fired at distinct distances.

Figure 3 - von Mises stress in mandible fired at 5 cm in each projectile caliber.

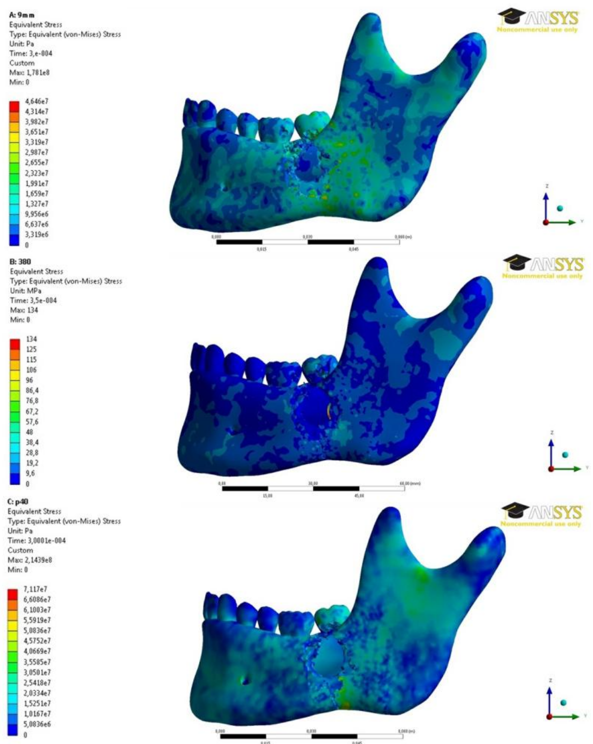
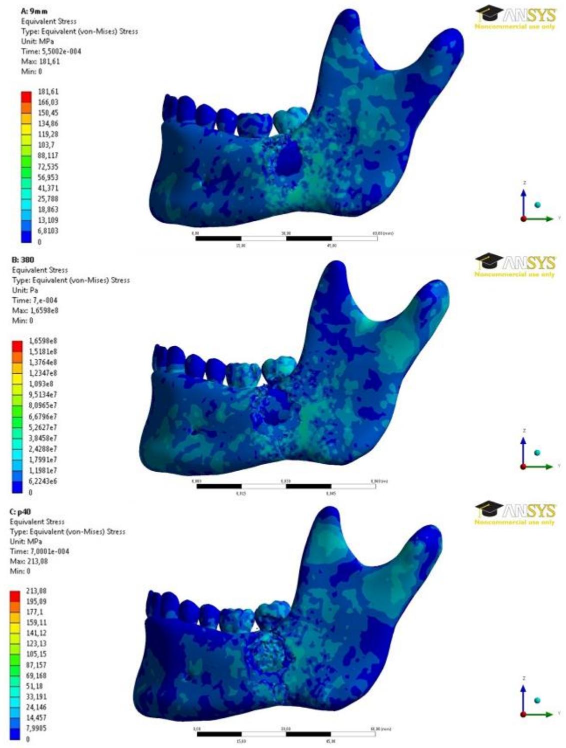


Figure 4 - von Mises stress in mandible fired at 15 cm in each projectile caliber.



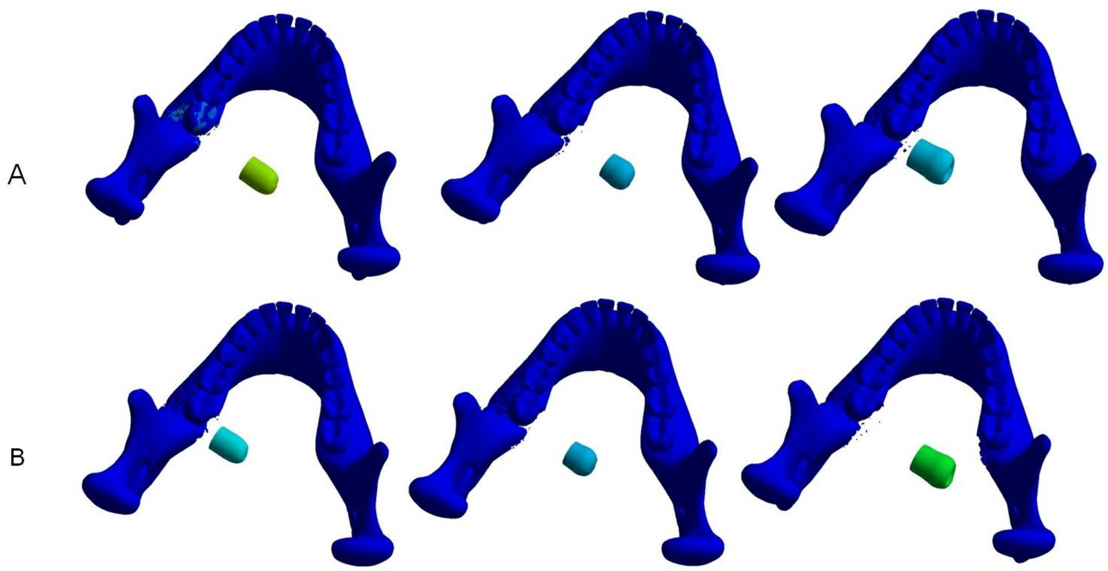
3. Energy loss

Energy loss of projectiles for the 9x19 mm Luger, .380-caliber and .40-caliber S&W fired at 5 cm were 90 J, 83.6 J and 135.96 J, respectively. The same projectiles fired at 15 cm exhibited energy losses of 91 J, 85 J and 138.4 J, respectively.

4. Projectile fragmentation, deformation and deviation

No projectile fragmentation was identified, and no significant deviation of the projectile trajectory was observed post-collision in samples fired at 5 and 15 cm. However, projectile deformations were observed in all cases (Figure 5). The .40-caliber S&W suffered the most deformation.

Figure 5 - Shape of the projectiles after hitting mandible. (A) Projectiles deformation after hiting mandible at 5 cm. (B) Projectiles deformation after hiting mandible at 15 cm.



Discussion

Finite element analysis in the ballistic field allows the simulation of the entry orientation and impact velocity of projectiles (10). The penetration of different projectiles may be simulated when the material parameters and geometrical shape of the projectile are available. Finite element analysis is a useful tool because of its flexibility. The model may be adjusted and used in countless ways. The use of this model is convenient, especially in the ballistic field, because it dramatically reduces ethical issues. This method enables the testing various hypotheses, including shifting projectile type, angle and velocity (4,9,10).

Finite element analysis appears to be a promising tool, but there are still some hurdles to overcome. The presence of soft tissues is one problem. Pintar *et al* (21) and Pintar *et al* (22) used a physical gelatin model to delineate the penetrating wound profiles of different projectile types. We recognize that the absence of soft tissues in finite element models of cranium bones may influence the results (4, 16, 19, 21, 23). Certain discrepancies between finite element results and real conditions are undoubtedly inherent to the methodology based on previous finite element models, which only contained hard tissue (24). Interactions of soft tissues likely play a dissipative role and absorb some of the energy from the impact, which reduces the wound diameter (23). The present study did not account for soft tissues, but the region of shot was chosen because the influence of soft tissues in the area was the lowest. However, we cannot exclude the possibility of minor changes in wound diameters in the presence of soft tissue.

The absence of soft tissue reproduction in the finite element models creates a strong research line: morphological analysis of entrance wounds by firearms. The investigation of bony orifices using a finite element perspective may aid in the reconstruction of a shooting scene (11).

Handguns create circular or oblong wound tracks when fired perpendicular to a target. All of the entrance wounds fired at 5 and 15 cm were round in our study, which is consistent with the literature (4, 10, 16). Entrance wounds are generally smaller than the diameter of the projectile (20), as observed in our study. However, projectiles fired from a distance less than 1 meter and accelerated by a propellant charge may cause a circular wound entrance with a wound entrance diameter that is equal to the projectile when soft tissues wounds are considered (25). Difficulties of caliber estimation from bone wound size are noted in the literature. Wound diameter is smaller than projectiles, but our results did not indicate a connection between wound diameter and caliber. The present study did not analyze exit wounds because soft tissues were not simulated. Analyses of exit wounds would be full of bias related to the absence of glands, tongue and muscles.

An inner beveling in cranium bones is suggestive of projectile entry wounds. Entrance wounds present a typical shape, i.e., round or ovoid, that has keen edges and a clear punched–out appearance (7). The mandible is part of the cranium, but it exhibits a distinct beveling behavior. Unusual shapes, such as triangular, nearly rectangular or irregular, were observed in bones such as the mandible and mastoid process (7). All of our entrance wound results displayed an external beveling, despite the round shape. Leaning and perpendicular shots also produce external beveling (7). Our results were similar, and the shots were simulated in a very close range, but the muzzles were not in contact with mandible.

The surface of full metal jacket projectiles is smooth along the entire projectile track, and the surface of contact with bone is small because of the pointed nose of the projectile. There is less displacement of bone fragments when these projectiles cause fractures (25). Our results demonstrated fractures in the mandibular basis in the .40-caliber S&W and .380-caliber fired at 5 and at 15 cm. The firing range was less than 1 meter, which delivered the maximum amount of kinetic energy to the bone tissues and broke the mandible bone. There was no release of bony fragments in any of the shots, which is consistent with the literature (4, 16, 19).

Partial metal jacket bullets and shotgun pellets can shatter bone and cause fractures of varying severity. The deformation of partial metal jacket ammunition is associated with an increased surface of contact between projectile and bone. Energy is transferred to a larger surface, which further deforms the projectile and increases static friction. The surface of full metal jacket projectiles is smooth along the entire projectile track, and the surface of contact with bone is small because of the pointed nose of the projectile (25). The 9x19 mm Luger may not have produced fractures because of its pointed-nose shape, which may have led to less energy transference and loss and the absence of fractures. Many projectiles are partially or fully sheathed with copper or soft steel alloy jackets. All projectiles in the present study were made of lead and jacketed with copper, which is a more resistant metal. Full metal jacket projectiles do not tend to fragment when they enter the body tissue, which creates different patterns of injury that can be clearly differentiated both clinically and radiologically (25). Our projectiles did not undergo any fragmentation, but there was deformation, especially in the .40-caliber S&W fired at 5 and 15 cm. Greater deformations of the .40-caliber S&W may be related to the largest energy loss and greater contact surface with the mandible bone.

Many projectiles are partially or fully sheathed with copper or soft steel alloy jackets. Full metal jackets are associated with projectile stabilization, deformation amount control (20), strength and deformation resistance (8). These projectiles also exhibit less displacement of bone fragments in fractures because of the smooth surface in the projectile path and the smaller surface contact of point nose projectiles (25). All of the projectiles in the present study were made with lead and jacketed with copper, which is a more resistant metal. Full metal jacket projectiles do not tend to fragment when they enter the body tissue, which creates different patterns of injury that can be clearly differentiated clinically and radiologically (25). The 9x19 mm Luger may not have produced fractures because of its pointed nose shape, which may lead to less energy transference and loss and the absence of fractures. Our results demonstrated fractures in the mandibular basis for the .40-caliber S&W and .380-caliber fired at 5 and 15 cm. The firing range was less than 1 meter, and a maximum amount of kinetic energy was delivered to the bone tissues, which broke the mandible bone. There was no release of bony fragments in any of the shots, which is consistent with the literature (4, 16, 19). Our projectiles did not undergo any fragmentation, but there was deformation, especially in the .40-caliber S&W fired at 5 and 15 cm. The greater deformations of the .40-caliber S&W may be related to the greatest energy loss and greater contact surface with the mandible bone.

The projectile destructive efficiency is measured by the rate of energy loss and the energy absorbed, which causes damage to the tissues (4). Our results indicated that the .40-caliber S&W had the largest energy loss and created the biggest mandibular destruction, which is consistent with the literature. The perforation made by this projectile was larger and had a wider bevel and two fracture lines. Comparisons with the other two simulated projectiles revealed that a smaller aperture resulted from the lower energy loss. The 9x19 mm Luger, which lost the smallest amount of energy, did not create fracture lines. The results for energy loss differed slightly between shooting distances.

Significant changes in stress distribution occurred near mandibular neck condyles and the mandibular notch. These findings coincide with the results of numerous investigations by Vollmer *et al* (15) and Santos *et al* (18). The mechanical response to traumatic situations was related to the width of the mandibular neck, which generated high stress levels on the same side as the traumatic load. The bone is narrower in the mandibular neck, so this region has less bone strength and a greater tendency to fracture (18). Our results support the following conclusions: morphological differences were observable in holes caused by three different incoming projectile calibers fired at different distances; larger deformations, apertures and bevels are related to greater amounts of energy loss, which is related to projectile properties, as expected in real conditions; and VMS distribution is stronger in mandibular neck condyles and the mandibular notch.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest.

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3 DISCUSSÃO

Enaltecendo a associação específica entre a análise de elementos finitos e a balística forense, é possível alcançar resultados bastante fidedignos, pois a representação de estruturas anatômicas e propriedades mecânicas são exatas. As análises permitem a simulação de projéteis distintos, com ângulo de entrada e velocidade de impacto diferentes. Aliado à reprodutibilidade confiável, o armazenamento dos resultados é viável (Zhen et al., 2012).

Foram relatadas diversas maneiras de validação da análise de elementos finitos aplicada à balística forense. O modelo de elementos finitos criado por Tang et al. (2012) e Zhen et al. (2012) foi validado por Chen et al. (2010), atirando em mandíbulas de porco. A validação do modelo da Universidade de Louis Pasteur, aplicado no estudo de Raul et al. (2008), consistiu no impacto de pêndulos em três cabeças de cadáveres humanos, descrito no estudo de Wellinger (1999). Pintar et al. (2000,2001) realizaram estudos prévios usando gelatina, a fim de delinear os perfis de penetração da lesão para diferentes tipos de projéteis. Os autores consideraram o modelo físico como dados de validação do seu modelo de elementos finitos. Entretanto, a validação mais próxima da realidade seria alcançada em tecidos humanos. Há algumas deficiências decorrentes de limitações éticas que restringem a utilização de cadáveres como modelos experimentais em dados de feridas de arma de fogo (Tang et al., 2012), assim, o modelo de elementos finitos do presente estudo não foi validado devido a limitações éticas óbvias, considerando a utilização de mandíbulas humanas e projéteis.

No presente estudo, um dos fatores que podem influenciar os resultados principais é a ausência de tecidos moles nos modelos de elementos finitos de ossos do crânio (Pintar et al., 2001; Mota et al., 2003; Chen et al., 2010; Tang et al., 2012; Zhen et al., 2012). Certas discrepâncias entre os resultados de elementos finitos e as condições reais são indiscutivelmente inerentes à metodologia baseada em modelos de elementos finitos prévios que contém somente tecidos duros (Stefanopoulos, 2013). Interações são esperadas, realizando um papel de dissipação, absorvendo energia do impacto, reduzindo, dessa forma, o diâmetro da lesão (Mota et al., 2003). O presente estudo não simula tecidos moles. A fim de minimizar esse viés, a região alvo do disparo foi escolhida devido à menor influência dos tecidos moles. Embora, não seja possível descartar a possibilidade de diâmetros menores de feridas, caso os tecidos moles estivessem presentes.

Pistolas disparadas perpendicularmente ao alvo criam feridas ovais ou alongadas (Cunningham et al., 2003). Corroborando com o que foi descrito na literatura, todas as feridas de entrada simuladas no presente estudo, disparadas a 5 cm e 15 cm foram arredondadas. Geralmente, as feridas de entrada são menores que o diâmetro dos projéteis, como foi observado no estudo em questão. Entretanto, projéteis, disparados a uma distância menor que um metro, podem causar ferimentos de entrada circulares com diâmetro igual ao do projétil, considerando tecidos moles (Stuehmer et al., 2009). Dificuldades na estimativa do calibre da ferida óssea são observadas na literatura. Embora o diâmetro da ferida seja menor que os projéteis, nossos resultados não inferem uma associação direta entre o diâmetro da ferida e calibre. Como tecidos moles não foram considerados no modelo construído por nós, o ferimento de saída não foi analisado, devido a possível tendenciosidade intrínseca da ausência de glândulas, língua e músculos.

A presença de um bisel interno em ferimentos de tecidos ósseos chatos estabelece um indício que permite identificar ferimentos de entrada no crânio (Quatrehomme e Iscan, 1998). Ao contrário, nosso resultado mostrou um bisel externo. A mandíbula, quando alvo de projéteis, apresenta um comportamento diferenciado (Quatrehomme e Iscan, 1998). O aparecimento de bisel externo pode indicar contato dos tecidos com a boca do cano da arma empregada no disparo (Quatrehomme e Iscan, 1998). Ainda que nossos resultados sejam semelhantes ao descrito, não houve simulação de contato com a mandíbula, e sim, a uma distância curta.

Todas as munições empregadas nas simulações do presente estudo eram encamisadas totais, sendo duas com pontas ogivais (9x19 mm Luger e .380), e uma com ponta plana (.40 S&W). Esse revestimento deixa a superfície do projétil mais lisa e as pontas ogivais reduzem o contato com o tecido ósseo. Dessa maneira, as fraturas causadas por esses tipos de projéteis possuem um menor desprendimento de fragmentos ósseos (Stuehmer et al., 2009). Nossos resultados mostraram que ocorreram fraturas na base da mandíbula pelos calibres .40 S&W e .380, disparados tanto aos 5 quanto aos 15 cm. Uma vez que o alcance do tiro foi inferior a um metro, uma quantidade máxima de energia cinética foi entregue aos tecidos ósseos, estabelecendo linhas de fratura no osso da mandíbula. A ponta mais fina do 9x19 mm Luger, em comparação às outras munições testadas, pode não ter permitido a ocorrência de fraturas, devido a uma menor dissipação e transferência de energia. Em concordância com a literatura, não houve qualquer libertação de fragmentos ósseos em qualquer dos tiros.

A camisa que reveste os projéteis os estabiliza e controla a quantidade de deformação provocada quando em contato com a vítima (Cunningham et al., 2003). No presente estudo, todos os projéteis foram feitos com chumbo e jaqueta de cobre, um metal mais resistente. Projéteis revestidos em metal tendem a não fragmentar quando penetram em tecidos do corpo, fazendo com que diferentes padrões de lesão que possam ser claramente diferenciados clínica e radiologicamente (Stuehmer et al., 2009). Projéteis encamisados são geralmente mais fortes e resistem à deformação ao encontrar um alvo (Berryman et al., 1995). De fato, nossos projéteis não foram submetidos a qualquer fragmentação. Por outro lado, houve deformação, especialmente no calibre .40 S&W disparado a 5 e 15 cm. Maiores deformações do calibre .40 S&W podem estar relacionadas a maior perda de energia e uma maior superfície de contato com o osso da mandíbula, já que sua ponta apresenta-se achatada.

O volume de gás que escapa do cano da arma depende do propulsor e, assim, correlaciona-se com a pressão de gás (Stuehmer et al., 2009). Nosso trabalho não levou em consideração o tipo de propulsor; pois o volume de gás não foi uma preocupação primordial para nós. Para lesões de contato ou de curta distância, o efeito do gás que é descarregado sob pressão na ferida também deve ser considerado. Este efeito é complicado para estimar, mas é importante para o tratamento de feridas, porque aumenta a contaminação da ferida e danos nos tecidos (Cunningham et al., 2003).

De acordo com a lei da conservação da energia, a energia que o projétil perde quando acerta a mandíbula é absorvida pela mesma. Portanto, quanto mais energia o projétil perde a medida que penetra na mandíbula, mais dano causa. A perda de energia reflete a eficiência destrutiva de um projétil atingindo um objeto. Portanto, quanto maior a perda de energia, maior a lesão (Tang et al., 2012). De acordo com a literatura, nossos resultados indicaram que o calibre .40 S&W teve a maior perda de energia e, consequentemente, deixou a maior destruição mandibular. A perfuração feita por este projétil foi maior, com biséis mais amplos e duas linhas de fratura. Comparando com os outros dois projéteis a perda de energia foi menor e consequentemente, o diâmetro da lesão. A munição 9x19mm Luger perdeu a menor quantidade de energia e nem sequer mostrou linhas de fratura. Resultados para a perda de energia pouco diferiram quanto à distância de disparo.

Mudanças significativas na distribuição das tensões ocorreram perto do côndilo mandibular e ao nível do colo da mandíbula. Estes resultados coincidem com os resultados de investigações numéricas descritas por Vollmer et al (2000) e Santos et al (2015).

4 CONCLUSÃO

Os estudos realizados permitem concluir que:

- Diferenças morfológicas foram observadas nos orifícios causados pelos projéteis testados, disparados à diferentes distâncias;
- Grandes deformações, aberturas e biséis estão relacionadas com uma maior quantidade de perda de energia, que por sua vez, estão relacionados às propriedades do projétil, conforme o esperado em condições reais;
- As tensões de von Mises são maiores no colo da mandíbula e incisura da mandíbula nos disparos simulados a 5 e 15 cm.
- Este estudo serve de base para que futuras pesquisas sejam realizadas associando biomecânica do crânio e balística forense.

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Stuehmer C, Blum KS, Kokemueller H, Tavassol F, Bormann KH, Gellrich NC et al. Influence of Different Types of Guns, Projectiles, and Propellants on Patterns of Injury to the Viscerocranium. J Oral Maxillofac Surg. 2009;67: 775-781

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ANEXOS

ANEXO 1: Certificação do Comitê de Ética

14/04/2015 Comitê de Ética em Pesquisa - Certificado

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 **"Análise dinâmica de elementos finitos de mandíbula humana com ferimentos produzidos por projéteis de arma de fogo a diferentes distâncias"**, protocolo nº 028/2013, dos pesquisadores Sarah Teixeira Costa e Felippe Bevilacqua Prado, satisfaz as exigências do Conselho Nacional de Saúde - Ministério da Saúde para as pesquisas em seres humanos e foi aprovado por este comitê em 06/06/2013.

The Ethics Committee in Research of the Piracicaba Dental School - University of Campinas, certify that the project **"Dynamic finite element analysis of the human mandibule with wounds produced by gunshots at different distances "**, register number 028/2013, of Sarah Teixeira Costa and Felippe Bevilacqua Prado, 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 Jun 06, 2013.

Prof. Dr. Felippe Bevilacqua Prado
Secretário
CEP/FOP/UNICAMP

Profa. Dra. Lívia Maria Andaló Tenuta
Coordenadora
CEP/FOP/UNICAMP

ANEXO 2: Comprovantes de submissão

Australian Journal of Forensic Sciences

Submission Confirmation

Print

Thank you for your submission

Submitted to
Australian Journal of Forensic Sciences

Manuscript ID
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Title
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Authors
Costa, Sarah
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ANEXO 3: Declaração

Declaração

As cópias dos documentos da minha autoria ou de minha coautoria, já publicados ou submetidos para publicação em revistas científicas ou anais de congresso sujeitos a arbitragem, que constam da minha dissertação de Mestrado intitulada "Simulação dinâmica por elementos finitos de ferimentos produzidos por arma de fogo na mandíbula humana" não infringem os dispositivos da Lei nº 9610/98, nem o direito autoral de qualquer editora.

Piracicaba, 19 de fevereiro de 2016.

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