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Dynamic simulation and finite element analysis of the human mandible injury protected by polyvinyl alcohol sponge

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ABSTRACT

There have been intensive efforts to find a suitable kinetic energy absorbing material for helmet and bulletproof vest design. Polyvinyl alcohol (PVA) sponge is currently in extensive use as scaffolding material for tissue engineering applications. PVA can also be employed instead of commonly use kinetic energy absorbing materials to increase the kinetic energy absorption capacity of current helmet and bulletproof vest materials owing to its excellent mechanical properties. In this study, a combined hexahedral finite element (FE) model is established to determine the potential protection ability of PVA sponge in controlling the level of injury for gunshot wounds to the human mandible. Digital computed tomography data for the human mandible are used to establish a three-dimensional FE model of the human mandible. The mechanism by which a gunshot injures the protected mandible by PVA sponge is dynamically simulated using the LS-DYNA code under two different shot angles. The stress distributions in different parts of the mandible and sponge after injury are also simulated. The modeling results regardless of shot angle reveal that the substantial amount of kinetic energy of the steel ball (67%) is absorbed by the PVA sponge and, consequently, injury severity of the mandible is significantly decreased. The highest energy loss (170 J) is observed for the impact at entry angle of 70°. The results suggest the application of the PVA sponge as an alternative reinforcement material in helmet and bulletproof vest design to absorb most of the impact energy and reduce the transmitted load.

1. Introduction

Firearm-related injuries over the past century are responsible for most of the morbidities and mortalities in the world [1,2]. Among the firearm-related injuries, more than 50% of all gunshot-related suicide attempts and nearly 14% of firearm-related assaults result in head and neck injuries [3]. This issue motivates scientists to focus on the basic mechanisms and principles of gunshot wound ballistics in the head and neck [4,5], including the maxillofacial region [6,7] for clinical, forensic, and military purposes. Since the maxillofacial region is an exposed part of the body, it is commonly subjected to gunshot wounds. Owing to the different entry angles of the bullet, maxillofacial gunshot wounds can result in serious injuries to the maxillofacial region and adjacent organs, which complicate the trauma [6,8]. However, present studies on the maxillofacial gunshot wounds have mainly focused on trauma treatment, repair, reconstruction, and finite element (FE) modeling of gunshot wounds. Almost no study has ever been performed any biomechanical analysis on a concept of design of a kinetic energy absorbing material to control the level of injury caused by gunshot to the human mandible. Therefore, it is desirable to develop a material that can be incorporated in helmet design to minimize the level of injury.

PVA sponge, which is currently in extensive use for the removal and management of diffuse fluids/blood at surgical site [9], can be considered as the most attractive kinetic energy absorbing material [10,11] owing to a combination of qualities, such as excellent mechanical strength and flexibility [12–17], availability, and relative cheapness [18]. Polyvinyl alcohol (PVA) is a synthetic polymer derived from polyvinyl acetate through partial or full hydroxylation. The amount of hydroxylation determines the physical characteristics, chemical properties, and mechanical properties of the PVA [19]. The structure of PVA is shown in Fig. 1. PVA sponges are formed from cross-linking of the linear polymers with tunable properties. At low polymer content, fluid freely moves through the matrix resulting in a soft compliant material. Increasing polymer content significantly stiffens and strengthens the matrix. However, the application of this versatile material so far has been limited to ophthalmic, plastic, and hand surgeries as a biocompatible biomaterial.

Recently, Karimi *et al.* [20] measured the Young's modulus (40 MPa) and maximum stress (9.79 MPa) of PVA sponge for the purpose of tissue engineering applications. The Young's modulus of PVA sponge at different the strain rates, including 1, 20, and 100 mm/min, resulted in 4.28, 208.33, and 187.51 MPa, respectively [21]. The Young's modulus of

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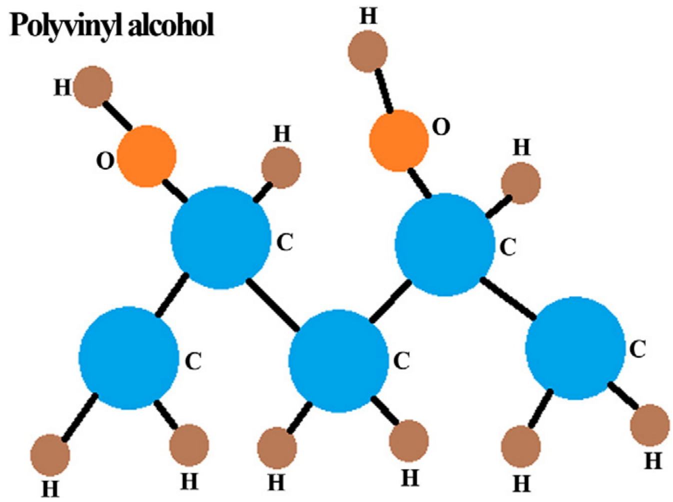

Fig. 1. The structure of polyvinyl alcohol.

PVA sponge in the longitudinal and circumferential directions was 38.91 and 33.34 MPa, respectively. The maximum stress, in addition, in the longitudinal direction was 17.90% greater than that in the circumferential direction [22]. The suitable mechanical properties of PVA sponge, especially under fast strain rates in different loading directions, would enable it to be used as an energy absorbing material for helmet and bulletproof vest design. However, a critical barrier to the use of the PVA sponge as energy absorbing material has been limited due to a lack of study on its kinetic energy absorption capacity. Very recently, Karimi *et al.* [10,11] conducted a dynamic finite element simulation study to compute the kinetic energy absorption capacity of PVA sponge. Their results suggested the suitable application of PVA sponge in helmet design to control the injury to the human head owing to trauma or concussion. Among the energy absorbing materials available in the market, expanded polystyrene foams (EPS) are typically employed for the design of the helmet liners [23,24], due to their capability of providing multidirectional resistance to impacts, combined with light weight and relatively low costs of production and suitable kinetic energy absorption capacity [25]. The EPS foam has the compressive Young's modulus and maximum stress of 6.5–39 and 0.51–1.50 MPa [23,25] as a function of thickness and density.

A way to improve the energy absorption properties of current helmets could be the use of non-conventional materials capable of higher energy absorption, while keeping the accelerations transmitted to the head and neck at a safe level. Thus, in this study, based on our previous three-dimensional finite element (3D FE) model of the human head damage mechanics in baseball, a 3D FE model of gunshot wounds to the human mandible is established to dynamically simulate the mechanism of mandibular gunshot wounds and the stress distributions in its various regions. FE analyses are executed through the LS-DYNA code under impact load to study the injury severity by gunshot having the steel ball with varying entry angles. After calculation, the injury severity of the mandible and the injury efficiency of the projectiles are compared to the mandible protected by PVA sponge.

2. Materials and methods

2.1. Material preparations and mechanical measurements

The preparation of the polyvinyl alcohol sponge has been thoroughly described in our previous studies [22,26,27]. Briefly, to prepare the PVA aqueous solution, 2 g of PVA (molecular weight = 40000, Sigma-Aldrich) was dissolved in 100 ml of distilled water at 50 °C under stirring at 400 rpm for 6 h. The polymer solution was then cast into cylindrical molds and freeze dried in order to obtain PVA spongy matrix. To improve its stability in water, the above sponge was cross-linked by exposure to the vapors of a glutaraldehyde aqueous solution (25%) at 37 °C for 24 h. After rinsed with distilled water, the sponge was freeze dried again. The final solution was poured into Petri dishes and allowed to stand at room temperature (25–30 °C) until cross-linking was completed (48 h). The initial dimensions of all prepared specimens were then measured precisely. The tensile test was performed using a uniaxial tensile test apparatus adapted for testing biological specimens [28–35]. All tests were performed at 25 °C and each sample was tested only once. A low strain rate of 5 mm/min which is typical for surgical procedures and gives more insight into tissue behavior was employed by the action of an axial servo motor [36–40]. In order to make sure about a firm fixation of samples between the jaws of the machine a small tensile pre-load was applied to each specimen. Moreover, rough sandpaper was used between the jaw and sample to assure no slip boundary [41–43]. The sample's length was measured after the application of the pre-load. This also helped minimize the bending effect caused by the weight of each specimen [44–46].

2.2. Finite element model

A 3D FE model of the human mandible was established using the explicit dynamics finite element code LS-DYNA 970 (LSTC, Livermore, CA, United States). The shape of human head and neck was obtained from Computed Tomography (CT) with an XY-resolution of 512 512 pixels. A total of 262 raw data images were obtained for the head and neck, including 85 data images of the mandible. The data were stored and exported in the Digital Imaging and Communications in Medicine (DICOM) format. Afterwards, these data were imported into a Windows-based computer using MIMICS, a specialized medical image processing software (MIMICS 10.0, Materialise Inc., Belgium) to create a surface mesh for the mandible. Following the selection of an appropriate threshold value for the "region growing" function of MIMICS, the integrated bone structure of the human head was separated from the soft tissue. The mandible was then isolated by selecting the "edit masks" function to form a new mask. After manual editing, the mask of the human mandible was converted into a 3D computer-aided design (CAD) model by using the "calculate 3-D" function. The original triangular surface mesh model of the human mandible was generated by the "remesh" module of MIMICS. By using several remeshing algorithms and user-specified parameters, the triangular mesh were reduced and reshaped to provide an even surface mesh. These surface-meshed models of the mandible were then imported into ABAQUS 6.10-1 (Dassault Systèmes Americas Corp, Waltham, United States) software for automatic net generation. The elements and nodes were partitioned based on the generated net.

The mechanical properties of PVA sponge [20], the human mandible and the steel ball [47] were assigned to the FE models. To obtain greater computational precision, hexahedral elements were used for the human mandible, sponge, and steel ball. To achieve a dynamic separation and spatter effect, the elements in the PVA sponge and angle region were selected for node release. The properties of boundary element of the surface mesh for the mandibular cancellous bone were used to determine the boundary between the cortical bone, cancellous bone, and sponge. Using the orientation of the surface mesh for the mandibular nerve canal, the region was generated by removing some of the internal elements of the model to make the model as resemble as possible to the actual anatomical situation. As with the 3D FE model of the human mandible, the teeth were not our primary concern in the current study, and it is assumed that they were part of the mandible and had the same mechanical properties as the cortical bone. The final model of the mandible was meshed with 275216 elements (30024 tetrahedral elements and 245192 hexahedral elements) and 1387101 nodes. PVA sponge along a steel ball was meshed with 14526 8-noded hexagonal elements besides 16805 nodes for 15 mm thickness. A FE model of a