An experimentally calibrated finite element study of maxillary trauma

Casas MJ, Krimbalis PP, Morris AR, Behdinan K, Kenny DJ. An experimentally calibrated finite element study of maxillary trauma.

Abstract – A baseball injury to an instrumented human cadaver maxillae was simulated with a regulation (142 g) baseball traveling at 14 m s^{-1}. Measurements of strain were obtained with three-axis strain gauge rosettes located at the medial palate and both canine fossae. A three-dimensional finite element (FE) model of a dentate human maxilla was constructed from computed tomography scans of the skull of an adolescent. This three-dimensional mathematical model of the maxilla was deemed geometrically accurate by convergence testing when the model's degrees of freedom approximated 74 000. The simulated load case involved a transient dynamic impact to the medial maxilla with boundary conditions imposed at skeletal buttresses of the model. The model was calibrated through direct comparison with the displacements and principal strains gathered from experimental and epidemiological data. The comparison of experimental and calculated principal strains as a result of the simulated impacts revealed a 1.7–11.4% difference.

Michael J Casas[1,2,3], Peter P Krimbalis[4], Alan R Morris[1,5], Kamran Behdinan[4], David J Kenny[1,2,3]

[1]Department of Research, Bloorview MacMillan Children's Centre, Toronto; [2]Department of Pediatric Dentistry, Faculty of Dentistry, University of Toronto, Toronto; [3]Department of Dentistry, The Hospital for Sick Children, Toronto; [4]Department of Aerospace Engineering, Ryerson University, Toronto; [5]Department of Rehabilitation Engineering, Faculty of Applied Science and Engineering, University of Toronto, Toronto, ON, Canada

Key words: dental; maxilla; impact; finite element; trauma

Michael J Casas, Staff Pediatric Dentist, The Hospital for Sick Children, 555 University Avenue, Toronto, ON, Canada M5G 1X8
Tel.: 416 816 8220
Fax: 416 813 6375
e-mail: michael.casas@sickkids.on.ca

Accepted 18 October, 2005

The biomechanical behavior of the maxilla and maxillary incisors during blunt projectile trauma is not well understood. Blunt projectile trauma to the face fractures teeth and surrounding bone, displaces teeth, tears soft tissue and produces damage and disability that lasts a patient's lifetime. Dental injuries produced by blunt projectile trauma such as knocked-out teeth, intrusions and extrusions produce outcomes that include pulp necrosis, root resorption, ankylosis, extraction, prostheses and dental implants (1–4). Some patients require general anesthesia and other specialized hospital services for acute management of these injuries and oral rehabilitation. Oral rehabilitation often entails multiple endodontic, surgical and prosthetic procedures. Maxillary incisors sustain 90% of all dental injuries (5). This was the basis of the decision to investigate the biomechanics of impact to the maxilla, the site of most damage.

Material and methods

Cadaver impact experiment

This investigation focused on impacts that replicate a significant number of sporting injuries that involve balls (baseball), pucks (road hockey) and collisions (squash racquet, lacrosse stick). A commercial ball-pitching machine (Ace '99 Pitching Machine; American Athletic Inc., Clive, IA, USA) was used to propel a regulation 0.142 kg baseball at 14 m s^{-1}, a velocity comparable with those measured in amateur baseball (6), at an instrumented cadaver head. Experimental data that were recorded included baseball velocity and acceleration as well as the forces, moments, strains and energy dissipation associated with the cadaver maxilla.

Impact damage produced by a baseball propelled at 14 m s^{-1} occurs within the first 0.44 ms; prior to

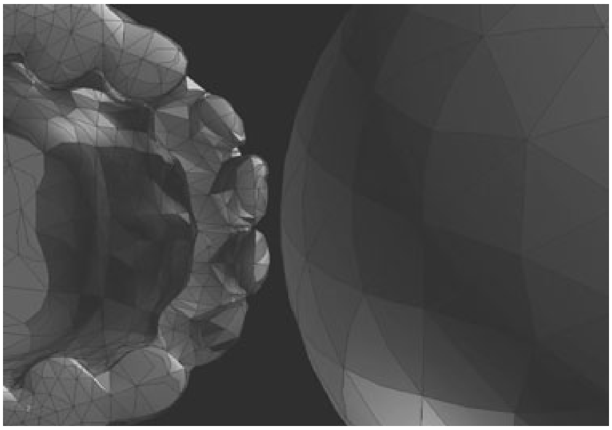

Fig. 1. Finite element mesh for experimentally calibrated model (73 848 degrees of freedom).

head recoil. Consequently, the cadaver head was rigidly mounted in a metal frame and secured by a series of stainless steel screws (7). Bone strains (tissue deformation) were measured using 350 ohm strain gauge rosettes (Vishay Measurements Group, Malvern, PA, USA) placed bilaterally on the anterior maxilla and mid-palate (Fig. 1). The strain gauge signals were amplified through Wheatstone bridge circuits (RDP Electronics Ltd., Wolverhampton, UK). The metal frame was attached to a 6-axis load cell (Bertec Corporation, Columbus, OH, USA) to measure impact force and energy received by the head. The baseball was repeatedly fired at an acrylic panel placed in front of the cadaver head until aim and velocity were correct and repeatable. The acrylic panel was removed and the ball was directed at the maxilla from a distance of 2 m. Speed was verified by a Speedchek radio frequency Doppler monitor (Outer Limits Inc., Edina, MN, USA). The pitching machine triggered two Nova high-speed 16 mm film cameras (Photo Kinetics Inc., New York, NY, USA) recording at approximately 1000 frames per second (with a film imprinted 1 kHz sync pulse) to record the impact from front and side views. Data from the load cell and strain gauges were recorded at 6 kHz per channel on two 16-bit analog to digital cards (Measurement Computing Inc., Middleboro, MA, USA) onto a PC laptop computer via a custom data acquisition program in Matlab v6.5 (Mathworks Inc., Natick, MA, USA).

Creation of the finite element model

A high-resolution 3D model of the maxilla that incorporated four separate maxillary incisors and two buccal tooth segments (canine to second molars) was constructed using Rhino v2.0 software (Robert McNeel & Associates, Seattle, WA, USA) from computed tomography (CT) scans (0.62 mm slices) of a fully dentate adolescent skull (female, age 12 year). Boundary contours were generated from segmentation of the CT scans using 3D Doctor software (Able Software Corporation, Lexington, KY, USA). Surfaces were constructed from grid attachments of a network of evenly spaced nodes at each successive boundary. Third order non-uniform rational B-splines enabled generation of smooth surface contours. Silicone molds of the teeth and investing bone and acrylic models were produced for verification of volumetric reconstruction.

Initial finite element (FE) meshing, application of boundary conditions and dynamic FE simulation were undertaken using MSC.Patran (MSC. Software, Santa Ana, CA, USA) as the pre- and postprocessor and MSC.Marc (MSC. Software) as the solver. An explicit solution was necessary to allow for time-varying boundary constraints, similar to other commercial applications of high-speed impact events (e.g. air bag deployment, bird strikes on aircraft). Meshes were created through subdivision of the constructed volumes into smaller volumes and meshed using 10 node tetrahedral elements. The final mesh populated the entire volume of the model, incorporating the geometry of each subdivision into a single, internally coarsened mesh with no violation of element aspect ratio and/or compatibility. The head fixture constraints were digitized using a Microscribe 3D digitizer (Immersion Corporation, San Jose, CA, USA). The digitized locations on the head fixture were then used as the location of the boundary conditions for the FEM. The simulated load case involved a transient, dynamic impact to the medial maxilla. The boundary conditions for the functional load case included constraining nodes for all degrees of freedom at the posterior and most superior extents of the model. These constraints are analogous to the manner in which the maxilla is suspended from the cranial base. Results were validated by a direct comparison with the displacements and principal strains gathered from experimental and epidemiological data.

In its final state, the solid model incorporated the maxilla, four separate maxillary incisors and two buccal tooth segments from canine to second molar. The solid model was then exported in Parasolid (.xmt) format (Parasolid, UGS PLM Solutions, Cambridge, UK), into a finite element preprocessor (MSC.Patran) MSC for mesh generation and implementation of the material properties, load case and boundary conditions. The load case was then solved by a processor (MSC.Marc) on a Dell Precision 650 Workstation with dual 3.2 GHz Xeon™ processors (Dell Corporation, Austin, TX, USA).

Convergence testing

The accuracy of the model was determined through a convergence test which is accepted as standard protocol for determining adequate mesh refinement in a typical FE model. In general, as an FE mesh becomes more refined, through an increase in its number of elements and nodes (degrees of freedom), its approximation to the exact solution converges towards a plateau value through a process called h-refinement (8). At some point, increases in degrees of freedom no longer translate to a significant change in displacement and to nodal variables (such as nodal displacements) and the final converged solution is obtained.

Material properties, boundary conditions and load case

Given the scarcity of fresh or frozen adult cadavers and less commonly available fresh or frozen adolescent or youth cadaver heads, we relied upon the automotive industry standard for crash simulations, embalmed adult human anatomical material. The use of fixed anatomic material also reduced the risk to investigators from splattered or aerosolized viral pathogens (e.g. HIV and hepatitis B and C) during handling and impact testing. In addition, the Research Ethics Board of The Hospital for Sick Children explicitly prohibited the use of child or adolescent postmortem human anatomical material by investigators appointed to The Hospital for Sick Children staff.

As the directionality of the distribution of material properties within the maxilla is not intuitive, assumptions based upon long bone experimentation would be arbitrary. The geometry of the maxilla does not reveal any tendency towards a particular axis or direction of principal strength. This characteristic, in conjunction with a lack of experimental data in the literature, led to the decision to assign isotropic material properties to the FE mesh. A FE model of occlusal forces applied to maxillary molars employed 22 GPa as Young's modulus for adult maxillary bone (9). Our adolescent model was assigned a Young's modulus of 11.0 GPa (E), Poisson's ratio of 0.3 (ν) and density 1800 kg m^{-3} (ρ) based on average literature values (10, 11). The boundary conditions for the functional load case included constraining nodes for all degrees of freedom at the posterior and most superior extents of the model. These constraints are analogous to the manner in which the maxilla is suspended from the cranial base. To simplify the model, the baseball was constrained such that it did not rotate and translation only occurred in the anterior–posterior direction. Similarly, in order to ensure that it was the maxilla that deformed and not the baseball, the baseball was assigned a Young's modulus an order of magnitude larger than the maxilla. The ball was given an initial velocity of 14 m s^{-1} and a separation distance from the medial maxilla of 2 mm for the initiation of the dynamic event.

Results

For the convergence test of this preliminary study, a series of five discrete FE models populated by 10-node second order tetrahedral elements were statically loaded and constrained at the most posterior and superior nodes of each model. Operator-specified mesh seeding allowed monitoring of displacements of three points common to all the meshes (a node on the medial palate and each of the canine fossae). When subjected to a static load acting on a single node located at the maxillary incisors, a clear monotonic convergence was revealed when the number of degrees of freedom approximated 74 000 (Fig. 1).

For the examined, transient dynamic load case, displacements were highly localized at the anterior portion of the maxillary incisors (Fig. 2). The comparison of experimental and calculated principal strains as a result of the simulated impacts revealed a 1.7–11.4% difference in magnitude. The results of the calculations of maximum principal

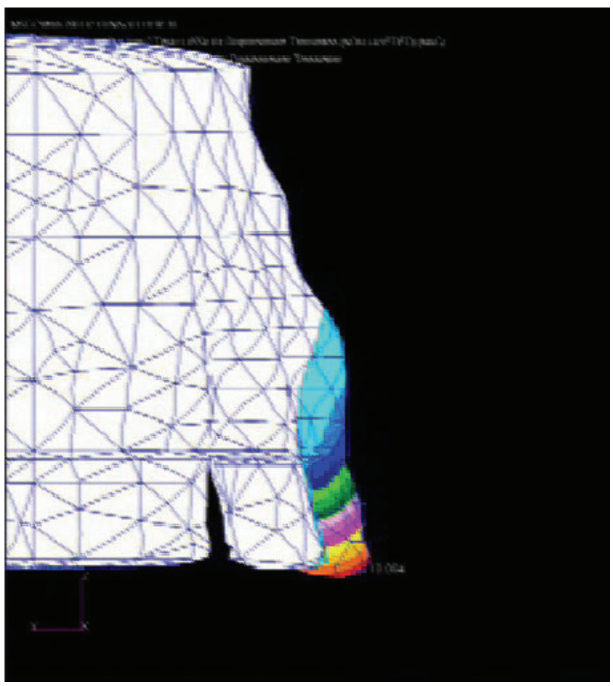

Fig. 2. Lateral view of modeled maxilla and incisors at during impact of baseball. The image of the baseball was removed from the image. Color banding (contours) of the incisors indicated differing strains calculated at each area of the incisors and adjacent bone.

Table 1. Relative differences between observed and calculated maximum principal strain values in two dimensions on the cortical surface of the human maxilla

Anatomical location within cadaver and model	Measured maximum principal strain in 2-D (ε)	Calculated maximum principal strain in 2-D (ε)	Percentage of measured value (%)	Relative error (%)
R. canine fossa	0.004243	0.004374	103.1	3.1
Medial palate	0.002371	0.0021013	88.6	11.4
L. canine fossa	0.003819	0.0038828	101.7	1.7

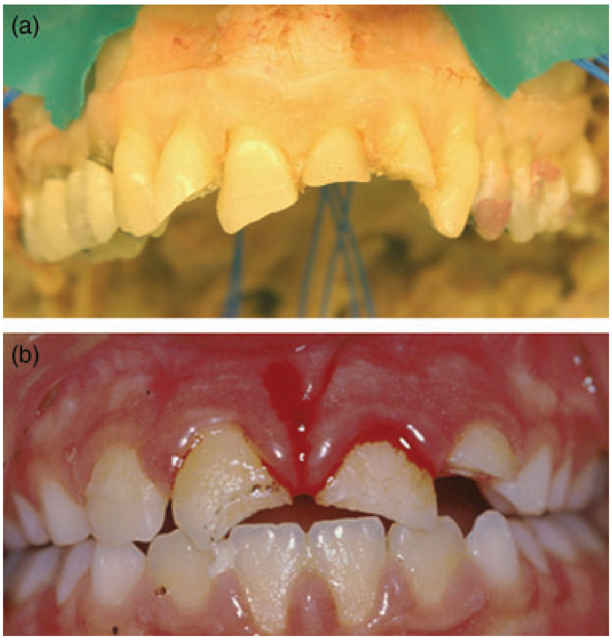

Fig. 3. A direct comparison of the crown fractures produced in the cadaver impact experiment (a) and a typical dental trauma experienced by an adolescent treated at The Hospital for Sick Children in Toronto, Canada (b).

strain in two dimensions from the impact experiment were compared with the values calculated from the FE simulation. The results of the comparison demonstrated a strong correlation with the experimental values with a maximum relative deviation of only 11.4% (Table 1).

Discussion

This is the first dynamic FE model of high velocity-low mass impacts to the maxillary incisors and alveolus of humans. Notwithstanding the relative simplicity of this FE model, satisfactory convergence between experimental and calculated strain values was achieved. The results demonstrated a qualitative similarity to the injuries observed and treated by clinicians on a daily basis. The isolation of the injury to the four maxillary incisors and two canines mimicked clinical observations of acute dental trauma. The region of impact and clinical presentation of the tissue damage confirms that experiment and the FE model have qualitatively replicated a typical injury (Fig. 3).

This preliminary model provides a valid foundation for future refinements that will allow testing of existing mouthguards and the development and testing of novel protective oral devices. Currently, the model consists of a single complex volume characterized by a single linear, elastic, isotropic material that represents maxillary bone and teeth. Model refinements underway include: (i) incorporation of tissue properties for dental hard tissues and increased anatomic detail of teeth, (ii) suspension of teeth in a periodontal ligament and (iii) incorporation of biomechanical parameters for bone and investing soft tissues. Testing will include assessments of bone transverse isotropy/anisotropy and substitution of mechanical properties of embalmed adult bone for those of vital adolescent bone. Accurate simulation of blunt projectile trauma to the maxilla will allow investigators to develop sports specific oral protection that will prevent or mitigate severe oral athletic injuries.

Acknowledgements – Based on a MASc thesis by Peter Krimbalis, Ryerson University, Department of Aerospace Engineering. This study was supported by a grant from Bloorview Children's Hospital Foundation, Toronto.

References

1. Barrett EJ, Kenny DJ. Survival of avulsed permanent maxillary incisors in children following delayed replantation. Endod Dent Traumatol 1997;13:269–75.
2. Humphrey JM, Kenny DJ, Barrett EJ. Clinical outcomes for permanent incisor luxations in a pediatric population: I. Intrusions. Dent Traumatol 2003;19:266–73.
3. Lee R, Barrett EJ, Kenny DJ. Clinical outcomes for permanent incisor luxations in a pediatric population: II. Extrusions. Dent Traumatol 2003;19:274–9.
4. Nikoui M, Kenny DJ, Barrett EJ. Clinical outcomes for permanent incisor luxations in a pediatric population: III. Lateral luxations. Dent Traumatol 2003;19:280–5.
5. Bijur P, Trumble A, Harel Y, Overpeck MD, Jones D, Scheidt PC. Sports and recreation injuries in U.S. children and adolescents. Arch Pediatr Adolesc Med 1995;149:1009–16.
6. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. J Biomech 1999;32:1371–5.

7. Crisco JJ, Hendee SP, Greenwald RM. The influence of baseball modulus and mass on head and chest impacts: a theoretical study. Med Sci Sports Exerc 1997;29:26–36.
8. Cook RD, Malkus DS, Plesha ME. Concepts and Applications of Finite Element Analysis, 3rd edn. New York: John Wiley and Sons; 1989.
9. Cattaneo PM, Dalstra M, Meslen B. The transfer of occlusal forces through the maxillary molars: A finite element study. Am J Orthod Dentofacial Orthop 2003;123:367–73.
10. Hart RT, Hennebel VV, Thongpreda N, Van Buskirk WC, Anderson RC. Modeling the biomechanics of the mandible: a three-dimensional finite element study. J Biomech 1992;25:261–86.
11. Currey JD. Bones: structure and mechanics. Princeton: Princeton University Press; 2002.