MEDICAL SCIENCE MONITOR

HUMAN ANATOMY

e-ISSN 1643-3750
© Med Sci Monit, 2014; 20: 1808-1813
DOI: 10.12659/MSM.892278

Received: 2014.08.19
Accepted: 2014.09.15
Published: 2014.10.03

Mechanical Properties of Cranial Bones and Sutures in 1–2-Year-Old Infants

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Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
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Source of support: The 12th Five-year National Plan for Science and Technology (No.2012BAK16B02), the Council of National Science Foundation of China (No. 81273338-81102300), the Scientific and Technological Key Project of Shanghai Municipality (No. 14231202500-14DZ2271500), the Shanghai Postdoctoral Scientific Program (No. 14R21423000)

Background: The mechanical properties of 1–2-year-old pediatric cranial bones and sutures and their influential factors were studied to better understand how the pediatric calvarium reacts to loading.

Material/Methods: Cranial bone and suture specimens were extracted from seven fresh-frozen human infant cadavers (1.5±0.5 years old). Eight specimens were obtained from each subject: two frontal bones, two parietal bones, two sagittal suture samples, and two coronal suture samples. The specimens were tested in a three-point bend set-up at 1.5 mm/s. The mechanical properties, such as ultimate stress, elastic modulus, and ultimate strain, were calculated for each specimen.

Results: The ultimate stress and elastic modulus of the frontal bone were higher than those of the parietal bone ($P<0.05$). No differences were found between the coronal and sagittal sutures in ultimate stress, elastic modulus, or ultimate strain ($P>0.05$). The ultimate stress and elastic modulus of the frontal and parietal bones were higher than those of the sagittal and coronal sutures ($P<0.05$), whereas the opposite ultimate strain findings were revealed ($P<0.05$).

Conclusions: There was no significant difference in ultimate stress, elastic modulus, or ultimate strain between the sagittal and coronal sutures. However, there were significant differences in ultimate stress, elastic modulus, and ultimate strain between the frontal and parietal bones as well as between the cranial bones and sutures.

MeSH Keywords: **Cranial Sutures • Fractures, Bone • Head Injuries, Closed • Infant**

Full-text PDF: http://www.medscimonit.com/abstract/index/idArt/892278

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Background

In forensic practice, it is difficult to distinguish between accidental and intentionally inflicted head trauma in an injured child. The key question is often whether the head injury was the consequence of a fall or a blow from caretakers suspected of child abuse [1,2]. Computer-based finite element modeling of the head can be used to simulate the events associated with traumatic head injury and quantify biomechanical responses within the brain, but the utility of these models depends upon the accuracy of cranial material property inputs [3]. Determining the material properties of pediatric bones and sutures, such as elastic modulus, ultimate stress, and ultimate strain, and elucidating the factors that affect them will not only provide insight into the reaction of the pediatric cranial bones and sutures to loading, but will improve the accuracy of computational and experimental models simulating falls or impacts to a pediatric head [4–7].

The dynamic material properties of human adult or animal skull tissues are well documented [8–16], but little information is available about the dynamic properties of human infant cranial bones and sutures [3,17,18]. Testing speed, strain rate, and cranial sampling position reportedly have significant effects on some or all of the computed mechanical parameters of adult cranial bones [7]. A modest correlation was also found between percent bone volume and the elastic modulus and the maximum bending stress [19]. Furthermore, the frontal bone (FB) was thicker and less porous and had a higher percent bone volume than the parietal bone (PB); thus, it fractured under higher forces and absorbed more energy prior to fracturing [20].

Coats and Margulies were the first to investigate pediatric bone and suture material properties at high rates (1.2–2.8 m/sec) related to fetal head molding in three-point bending and tension. They found that pediatric cranial bone is 35 times stiffer than pediatric cranial suture. In addition, pediatric cranial suture deforms 30 times more before failure than pediatric cranial bone. The PB was found to be significantly stiffer and have a higher ultimate stress than occipital bone [18]. McLaughlin et al. reported no significant difference in ultimate stress at failure between the coronal and sagittal sutures of 1-week-old Wistar rats. The stiffness of the coronal and sagittal sutures was also comparable. The elastic modulus of coronal and sagittal sutures was 13 Mpa and 14 Mpa, respectively, while the estimated ultimate strain values were 160% and 120% for the sagittal and coronal sutures, respectively. However, no data currently exist in the literature regarding whether there is a difference in the material properties between coronal and sagittal sutures of human infants [21]. Few studies have reported differences in bending properties

The purpose of this study was to examine the differences in the material properties of human infants (1–2 years old) in different bone and suture sampling positions. These results could be used in future computational models simulating the infant head during accidental and intentionally inflicted impact.

Material and Methods

The cadaver specimens were obtained from deceased infants donated by their families to the Southern Medical University in China. The research was approved by the ethics committee of Southern Medical University.

Specimen preparation

Human infant cranial bones and sutures were obtained from seven fresh-frozen human infant cadavers (females, three; males, four; 1.5±0.5 years old). All materials were thoroughly examined to ensure a lack of skull fractures and malformations and refrigerated at –20°C until the preparation and testing, thus minimizing the number of freeze-thaw cycles to prevent bone damage. We then thawed out the subjects in saline no more than 6 hours before the experiment. Eight specimens (6 cm long, 1 cm wide) were obtained from each subject: two FB, two PB, two parietal–parietal suture (sagittal sutures) samples, and two parietal–frontal suture (coronal sutures) samples. The latter two contained suture and bone. We used a vertical band saw and gently filed the cut faces to ensure accurate dimensions. The positions and directions of the samples from the eight skulls were kept as uniform as possible to allow for realistic future comparisons (Figure 1). The thickness of each suture was measured using a vernier caliper. The width and thickness of each test specimen were measured adjacent to the cross-section where the fracture occurred.

Mechanical testing

The samples (n=56; eight each from seven infant cadavers) were subjected to a three-point bending test using a BOSE material testing machine (ELF-3510AT; Bose, Inc., Chicago, USA) at 1.5 mm/s after micro-computed tomography measurements. Each specimen was thawed at room temperature in saline no more than 4 h prior to testing. Prior to testing, each specimen was instrumented with support structures (Figure 2) made from a rigid two-part epoxy resin to prevent erroneous slippage during testing and provide a flat surface on which to rest the specimens. This reduced the effective span length for the tests to 4 cm (the distance between the two epoxy supports) but still allowed specimen rotation and bending. All data were collected using the computer data acquisition system consisting of the BOSE material testing machine and a computer.

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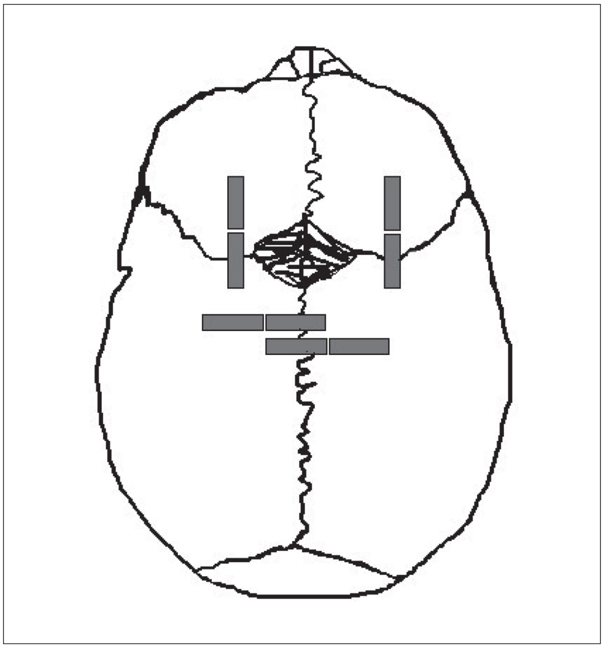

Figure 1. Schematic indicating the locations of the pediatric cranial bone and suture specimens. Two parietal bone and two frontal bone specimens were removed from the skull along with two parietal-parietal sutures (sagittal suture) and two frontal-frontal sutures (coronal suture, superior view).

Data analysis

During the mechanical testing, the force-displacement curves of the 56 tested specimens were recorded. The elastic modulus, ultimate bending stress, and ultimate strain were then calculated.

The Euler-Bernoulli beam theory is applicable only in cases in which the ratio of span length to thickness is at least 8 [22]. In our study, the average span length to thickness ratios of the tested specimens was >8. Therefore, the Euler-Bernoulli equation could be used to calculate the elastic modulus (*E*):

$$E = \left(\frac{F}{\delta}\right)\frac{L^3}{48I} \quad (1)$$

where F/δ is the force-displacement ratio in the linear elastic region of a three-point bending trace (Figure 3), L is the span of the beam, and I is the moment of inertia of the rectangular cross-section of the beam [23].

The flexural strain (ε_f) from three-point bending was calculated from the relationship:

$$\varepsilon f = \frac{6t\delta}{L^2} \quad (2)$$

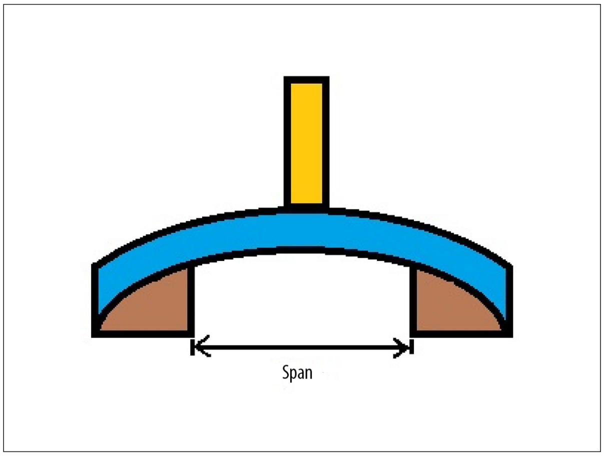

Figure 2. A local photo of the test setup schematic used in this study indicating a sample specimen instrumented with support structures.

where δ is the maximum deflection in the center of the beam, t is the thickness of the sample, and L is the span. Ultimate strain (ε_{ult}) was selected as the flexural strain corresponding to the ultimate stress.

In-plane stress (ε_{xx}) was calculated using Timoshenko's corrected version of the beam theory equation, which accounts for radial tensile forces within the beam as the result of an applied concentrated load to the center of the beam:

$$\sigma_{xx} = \frac{3FL}{8wc^3}y - 0.133\frac{F}{wc} \quad (3)$$

where F is the measured force, w is the width of the specimen, L is the span, c is half of the thickness, and y is the location of interest along the y-axis (outer surfaces at y=±c) in the center of the beam. The ultimate stress (ε_{ult}) is then calculated using the maximum force for F in equation (3).

Statistical analysis

The data are presented as mean ±SD. The statistical significance of the differences between groups was determined by one-way analysis of variance followed by Student-Newman-Keuls post hoc multiple comparison tests (two-means comparison). Correlations were measured using the Pearson coefficient and two-tailed P values. The significance level for all analyses was set as P<0.05 and all statistical analyses were performed using SPSS 21.0 (SPSS, Inc., Chicago, IL, USA).

Results

According to the calculated mechanical properties of PB and FB (Figure 3), both ultimate stress and elastic modulus in

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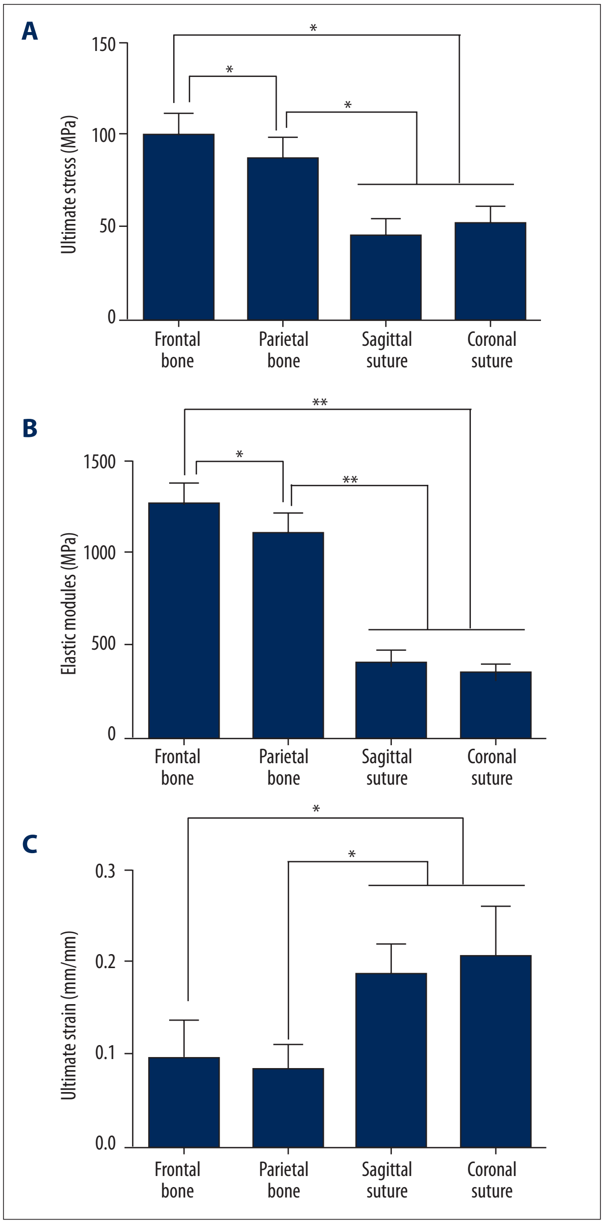

Figure 3. Comparison of the calculated mechanical properties of the human parietal bone, frontal bone, sagittal suture, and coronal suture in the three-point bending test: ultimate stress (**A**), elastic modulus (**B**), and ultimate strain (**C**) by analysis of variance.

FB (99.75±11.08 MPa and 1265.65±120.90 MPa, respectively) were higher than those in PB (87.12 ± 10.58 MPa, *P*<0.05 and 1103.01±112.77 MPa, *P*<0.01, respectively). No significant difference was found in ultimate strain between PB and FB (*P*>0.05 for both).

The order of ultimate stress and elastic modulus from high to low in different positions of cranial bone was: FB (99.75±11.08 MPa and 1265.65±120.90 MPa, respectively) >PB (87.12±10.58 MPa and 1103.01±112.77 MPa, respectively) > coronal suture (52.44±8.71 MPa and 354.83±44.86 MPa, respectively) > sagittal suture (44.75±10.13 MPa and 408.12±59.08 MPa, respectively). The order of ultimate strain from high to low was: coronal suture (0.2085±0.0529 mm/mm) > sagittal suture (0.1876±0.0348 mm/mm) > FB (0.0972±0.0424 mm/mm) > PB (0.0866±0.0270 mm/mm).

Significant differences were found in ultimate stress, elastic modulus, and ultimate strain between cranial bones (PB, FB) and cranial sutures (sagittal suture, coronal suture, *P*<0.01 for elastic modulus between both FB, PB and sagittal suture, coronal suture; *P*<0.05 for all others). No significant difference was found in ultimate stress, elastic modulus, or ultimate strain between sagittal and coronal sutures (*P*>0.05 for all).

Discussion

A few human infant finite element models have been constructed to perform a series of virtual experiments [6,24–29]. However, there has been no FE model for infants aged 1–2 years until now. An important reason for this is that no mechanical properties are documented for 1–2-year-old infants. The aim of this paper is to study the mechanical properties of the cranial bones and sutures of 1–2-year-old infants to better understand how the pediatric calvarium differs from that of adults under loading stress [15,21].

Although the mechanical properties of adult cranial bone including ultimate stress and elastic modulus did not differ, it was reported that pediatric cranial bones <13 months old were significantly stiffer and have a higher ultimate stress than occipital bone [17]. However, no studies have reported the differences in material properties between human infant PB and FB, while few studies have reported the material properties of human pediatric cranial sutures, especially in 1–2-year-old infants [30].

In our study, the ultimate stress and elastic modulus values of the FB were higher than those of the PB, which was consistent with the findings of Coats and Margulies in which both ultimate stress and elastic modulus differed between the PB and occipital bone. This result might be related to the fact that the average FB thickness was greater than that of the PB [17]. In addition, the ultimate stress of the PB was higher than those of the sagittal and coronal sutures. The elastic modulus of the PB was also higher than those of the sagittal and coronal sutures, while the ultimate strain of the PB was lower than those of the sagittal and coronal sutures. Sutures are more energy absorbent than cranial bone [31]; thus, they are able to reduce the amount of stress experienced by the surrounding bones [32]. This effect is partially

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due to the much lower Young's modulus of the suture than of the bone, which allows the suture to act as a cushion within the skull [33].

Whether there are differences in the material properties of the human pediatric cranial suture remains unknown. These data are also important in the development of an accurate pediatric head injury computational model. As was reported that pediatric PB and occipital bones had different material properties such as ultimate stress and elastic modulus, we wondered whether the material properties would differ from coronal and sagittal sutures [15]. To our surprise, we found no significant difference between coronal and sagittal sutures in ultimate stress, elastic modulus, or ultimate strain. McLaughlin et al. demonstrated that sagittal and coronal sutures in 7-day-old rats had elastic moduli of 13 and 14 MPa, respectively. The difference was not significant, however, which was in very good agreement with the results of the present study. Besides, their result was obtained in rats, which differ from humans [15]. Since location plays an important role in ultimate stress and elastic modulus, skulls should not be considered homogeneous in the creation of computational models to investigate impact events in pediatric head trauma [17].

However, our study has some limitations. First, the data were obtained from only seven subjects, which is a small sample. Second, the assumptions that were made about the geometry of each bending specimen were not large enough to be significant. The analysis method used in this paper assumed that each specimen behaved like a linear beam of a uniform cross-section. Although it was observed that the bone samples from different individuals were curved in the same direction, the initial radius of curvature was eight times greater than the thickness of each specimen.

Despite these limitations, our results provide a valuable reference for relevant research. To the best of our knowledge, the current mechanical data in the literature do not include studies on the differentiating mechanical response of 1–2-year-old pediatric cranial sagittal and coronal sutures on the mechanical properties of pediatric cranial bones and sutures. The results of our study might extend the scope of our knowledge and aid further studies of the mechanical properties of 1–2-year-old infant cranial bones and sutures.

Conclusions

This study examined the effects of cranial sampling position and bone microstructural parameters on the calculated mechanical properties of pediatric cranial bones and sutures. Several conclusions can be drawn. First, ultimate stress and elastic modulus values of the FB were higher than those of the PB in 1–2-year-old infants. Second, no differences were found between coronal and sagittal sutures in terms of ultimate stress, elastic modulus, or ultimate strain. Third, the ultimate stress and elastic modulus values of the FB and PB were higher than those of the sagittal and coronal sutures, while the ultimate strain findings were opposite.

Conflict of interest statement

None of the authors have any conflict of interest in this publication.

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