BIOMECHANICAL AND HISTOLOGICAL EVALUATION OF THE FETAL CALF SKULL AS A MODEL FOR TESTING HALO PIN DESIGNS FOR USE IN CHILDREN

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ABSTRACT

PMT-type halo pins were driven into 43 samples of skull bone taken from eight fetal calf skulls (30–39 week gestational age). Bi-linear force-penetration curves were obtained, consisting of a low initial stiffness region, associated with elastic deformation of the diploë, and a secondary linear region with high stiffness, associated with consolidation of the diploë and pin penetration. Radial compression of 11 samples demonstrated a Young's modulus of 15–139 MPa, a 2% offset yield stress of 1–5 MPa and a consolidation modulus of 188–479 MPa. These results suggest that skull thickness cannot be reliably used to predict halo pin penetration loads, at least not in the fetal calf skull. Histologically, the fetal calf skull is more like a four-year old child than a neonatal child. The relevance of the fetal calf skull to human infants and children remains inconclusive due to the lack of available mechanical property data in the radial direction for skull bone from human infants and children.

INTRODUCTION

A halo orthosis, consisting of a halo ring, pins, frame and rigid body vest is a standard means of immobilizing the cervical spine. Halo pins are screwed into threaded holes in the ring until the unthreaded pin tips penetrate the skin and into the outer table of the skull bone. Halos are designed for use in adults, but are also used for children and infants. Torque levels required to attach halo pins are related to friction at the threads between the ring and the threaded pins, flexural stiffness of the ring, strength and thickness of the skull bone, and pin tip design. Torque levels that are appropriate for use in an adult are most likely excessive for young children and infants and can result in the pin penetrating through the inner table of the skull bone.

The objectives of this study were (a) to determine if skull bone thickness can be used to reliably predict penetration loads; and (b) to explore the fetal calf skull as a potential animal model for testing halo pin designs for use in children, in terms of skull bone histology and biomechanics.

MATERIALS AND METHODS

Eight fetal calf skulls were used to prepare 43 samples for pin penetration testing and 11 for compressive mechanical property determination. The gestational age of each fetus was estimated from the crown-to-rump length measured at the slaughterhouse.

A coping saw and Dremel tool were used to excise as many 2-cm x 2-cm samples as possible. Bone thickness was determined using a digital micrometer with 2-mm diameter measuring faces (Brown & Sharp AD series) and the location of measurement marked on the dermal surface with an ink dot.

A Sintech 5/G electromechanical test system was used with a 20 kN load cell with 0.5 N preload and a 30 Hz data acquisition rate, and 2 mm/min loading and unloading speed. Precision of the load cell was 0.5 N at 100 N and 5 N at 1000 N. Displacement of the crosshead was measured with an optical encoder (precision of 0.1 mm).

Bone samples were embedded in dental "green stone" (Jade Stone, Whip Mix Corporation, Louisville, Kentucky), with a folded piece of aluminum foil attached to the dural surface. Dental stone provided uniform support to the irregular dural surfaces and to the four cross-sectional cut surfaces of the skull pieces. An aluminum foil tab protruded through the dental stone, from the side of the sample.

A total of 43 samples were tested using 8 PMT pins (PMT Corporation; Chanhassen, MN), with a 4.8-mm long and 4.8-mm diameter flange tip, with concave flange shoulders. Skull samples with a thickness greater than 6-mm were not used for the penetration tests in order to limit the study to the human skull thickness range found in children [1]. The PMT pins were used in rotating order so as to use each one no more than 6 or 7 times for all testing, including preliminary trial tests. An ohmmeter was used to measure the resistance between the pin and the substrate aluminum foil. Each test was carried out until electrical contact between the pin and the aluminum foil indicated penetration through the inner table.

For the compressive mechanical property tests, eleven 6-mm x 6-mm skull specimens were cut with a diamond blade. The dural and dermal surfaces were trimmed to provide two flat and parallel faces and compression was carried out at 0.5 mm/min in the radial direction using one fixed flat steel platen and one flat steel platen with a spherical bearing. Teflon tape was used between the bone surfaces and the steel platen surfaces to minimize friction. An extensometer was used to measure displacement between the platen faces. Young's modulus in the radial direction was calculated from the slope of the steepest part of the elastic segment of the stress-strain curve. Zero strain was defined as the intersection of the Young's modulus regression line and the strain axis. The yield stress was determined as the 2% offset stress. Seven of the eleven samples were tested beyond the yield point into the consolidation range, by testing until the platen-platen strain exceeded 75% strain. The consolidation modulus was defined as the steepest part of the curve after the 2% offset yield stress.

One fetal calf head was immersed in formalin for 3 months. A 2 x 2 cm piece of skull bone and the overlying dermal tissue was removed and processed using standard soft tissue embedding techniques in paraffin, after decalcification in 5 percent nitric acid. Several 3 x 3-cm samples were removed so as to retain the overlying dermal tissue. Four different halo pin types (HiFix, Jerome, PMT and Bremer) were driven into the pieces of skull with a screw driver using a special jig [2], until a load value was reached, corresponding to the force predicted for the sample skull thickness from a nonlinear regression fit of "load at electrical contact" versus thickness. After waiting 15 minutes to allow for stress relaxation, the load was reapplied. After another 15-minute period of stress relaxation, the pin was removed and the sample was processed for histology, as described above.

RESULTS AND DISCUSSION

Load-displacement plots of the PMT pin were of bilinear form with a low initial stiffness associated with elastic deformation of the diploë, and a secondary linear region with high stiffness, associated with consolidation of the diploë and porous inner and outer tables. Confirmation of pin penetration by electrical contact between the pin tip and the aluminum substrate foil occurred at a slightly larger value (0.6-mm) of penetration than the measured skull thickness prior to testing. This offset may have been due to the observed bulging of the inner table directly under the pin, occurring prior to actual piercing of the periosteal layer by the pin. The relationship between electrically determined penetration depth and initial skull thickness was linear ($R^2 = 0.94$, $p < 0.0001$), with a slope of 0.98. A relationship was established between the load recorded (F) in Newtons at a pin-penetration depth equal to the original skull thickness (T), and the original thickness in mm, as follows:

$$F = 100 + 4.3\, e^{T} \qquad (1)$$

This relationship has a modest goodness of fit of $R^2 = 0.76$, $p < 0.0001$, but has wide 95%-confidence intervals, for estimating penetration load from skull thickness. For example, the 95% limits on predicted penetration loads for a skull thickness of 1.5 mm are 0–475 Newtons, and for a thickness of 4 mm, 0–700 Newtons.

The compression tests (Table 1) produced stress-strain curves with an initial linear region, followed by a plateau at 3–10% strain (platen-platen engineering strain), and a consolidation region beginning at about 30–50% strain. Direct comparison of human and calf skull bone properties is not possible, because of differences in testing techniques and directions of loading. Our data fall in the range of yield stress and Young's modulus values derived from three-point bending tests of late-term fetal and neonatal human skull bone [3,4]. These properties, however, apply to the circumferential direction. No comparable human infant or child data exist for the radial direction.

Histology of the fetal calf skull showed the bone to be lamellar with an inner and outer table and a trabecular diploë layer. The thickness of the diploë layer was roughly equal to the combined thickness of the inner and outer tables. There was variation in the structure of the tables from site to site, which may explain the wide 95% confidence intervals for predicting penetration load from skull thickness. In human infants, the cranial vault is unilaminar until the age of about four, when the diploë layer and two tables appear [5]. The histology of the samples penetrated by the various halo pin types showed progressively increasing damage in the following order: HiFix, Jerome, PMT, and Bremer.

Table 1. Fetal Calf Cranial Bone Compressive Mechanical Properties in the Radial Direction

	Sample Size	*Mean (SD)*	*Range*	*95% Confidence Interval*
Young's Modulus (MPa)	11	69 (43)	15–139	40–98
2% Offset Yield Stress (MPa)	11	3 (2)	1–5	2–4
Consolidation Modulus (MPa)	7	296 (106)	188–479	198–394
Crown-Rump Length (cm)	11	67 (7)	61–86	62–72
Estimated Gestational Age (Weeks)	11	32 (3)	30–39	30–34

CONCLUSIONS

While a statistically significant regression fit was determined between the calf skull thickness and the penetration load of a PMT pin, wide 95% confidence limits indicate that using skull thickness may not provide a reliable means to predict penetration loads, at least not in the fetal calf skull model. The relevance of the fetal calf skull model to human infant skull bone remains inconclusive, due to the lack of available mechanical property data in the radial direction for human infants and children.

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