

# Material Properties of the Inner and Outer Cortical Tables of the Human Parietal Bone

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## ABSTRACT

Even though the cranial vault functions as protection for the brain and as a support structure for facial and masticatory functions, little is known about its mechanical properties or their variations. The cranial vault bone is interesting because of its maintenance in spite of low functional strains, and because calvarial bone cells are often used in cell culture studies. We measured thickness, density, and ash weight, and ultrasonically determined elastic properties throughout the cortices of 10 human parietal bones. The results are unique for studies of the cranial vault because: 1) measurements focused specifically on the cortical components, 2) the orientations of the axes of maximum stiffness were determined before measurement of elastic properties, and 3) two related measurements (bone density and percent ash weight) were compared. Results showed that the periosteal cortical plate (outer table) and the endosteal cortical plate (inner table) had significant differences in material properties. The outer table was on average thicker, denser, and stiffer than the inner table, which had a higher ash weight percentage. Within each table there were significant differences in thicknesses, ash weight percentages, and  $E_2/E_3$  anisotropies among sites. Few sites on either table had significant orientations of the axes of maximum stiffness. Despite this apparent randomness in orientation, almost all sites exhibited anisotropies equivalent to other parts of the skeleton. *Anat Rec* 268:7–15, 2002. © 2002 Wiley-Liss, Inc.

**Key words:** cranial vault; diploë; elastic properties; material properties; bone density; bone ash weight; parietal bone

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Although research has increased our knowledge of adult remodeling and microstructure of the craniofacial skeleton (Enlow and Harris, 1964; Enlow, 1966; Boyde et al., 1990; Merida-Velasco et al., 1993), little is known regarding regional variations and growth changes in cortical material properties and their microstructural correlates. Yet, cortical material properties are important for understanding the relationship between the function and mechanics of the craniofacial skeleton, and may be an important link between functional loading, microstructure, and adaptation in cortical bone.

A few studies have examined material properties of cortical bone in the human mandible (Ashman and Van Buskirk, 1987; Carter, 1989; Arendts and Sigolotto, 1990; Dechow et al., 1992), but little information is available on other craniofacial regions (Dechow et al., 1993). These regions are of great interest, not only because of their

importance in orofacial functions, such as mastication, but also because they can provide crucial information on bone adaptation in regions of diverse function.

The cranial vault is diploic bone consisting of two cortical plates—the internal and external laminae (inner and

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outer tables) (Sicher and DuBrul, 1970)—sandwiching a layer of trabecular bone known as the diploë. The vault has a unique gross structure that functions to protect the brain and historically has served as a linchpin for the functional matrix hypothesis of skull growth (Moss, 1968).

A prominent functional feature of the cranial vault is the very low strain engendered by biting or mastication (Ravosa et al., 2000). Low functional strains suggest that the cranial vault is overbuilt for absorbing muscular and masticatory loads, and that its structure is maintained for protection of the brain. The mechanism of this maintenance is unknown, but the low strains suggest that the role of mechanical loading is less important in this area than in other parts of the skeleton.

It is likely that there are important differences between the inner and outer tables of the cortical bone, as the outer table is oriented to the external environment and directly bears muscular loads, while the inner table is in contact with the brain and its dural coverings. How the mechanical properties and morphology of the cortical bone of the cranial vault reflect these unique functions is the central question of the present work.

Several studies (Evans and Lissner, 1957; McElhaney et al., 1970; Evans, 1973) have described mechanical characteristics of the cranial vault bone. These studies focused on mechanical tests of structural features by using specimens that included both cortical tables and the diploë. There is little information regarding the mechanical characteristics of the cortical components of the parietal or other cranial vault bones. Portions of the outer table serve as anchorage for masticatory and nuchal musculature, and locally bear significant loads (Behrents et al., 1978). Preliminary studies of the cortical structure of human parietal and frontal bones (Peterson and Dechow, 1995, 1996; Peterson et al., 1997) were surprising because most specimens from both tables exhibited some anisotropy. An earlier investigation (Dechow et al., 1993) found little anisotropy in supraorbital bone, but did not use a technique designed to evaluate the principal directions of stiffness in the cortical specimens.

Our immediate objective was to characterize the cortical material properties of the human parietal bone. This knowledge should aid in formulating hypotheses about the relationships between mechanical properties, function, and microarchitectural structure in the skull, and how these relationships may differ from those found in better studied areas of the skeleton, such as the diaphyses of long bones. In particular, we are interested in differences between the inner and outer tables or cortical plates, because of possible differences in function and structure.

## MATERIALS AND METHODS

Bone specimens were removed with a trephine bur (Nobelpharma, Göteborg, Sweden) from five dry calvaria and five unembalmed, fresh-frozen whole cadaver heads. A random mix of subjects of both sexes ranging in age from 58 to 88 years of age was studied. Specimens were not collected from cadavers known to have died from primary bone diseases. Demographic information was lacking for some specimens from dry calvaria. Fresh crania were stored in freezers at  $-10^{\circ}\text{C}$  prior to removal of bone specimens. The freezing process has a minimal effect on the elastic properties of the bone (Evans, 1973; Dechow and Huynh, 1994; Zioupos et al., 2000). Drying of bone increases stiffness (Evans, 1973), although we have found

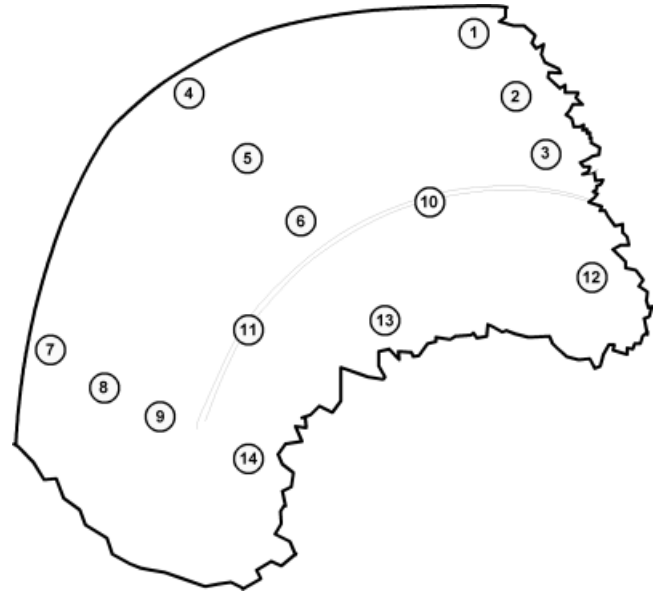


Fig. 1. Locations of cortical sites from the outer and inner tables of the parietal bone.

that rehydration of dried mandibular bone specimens actually results in a small decline in elastic modulus compared to the modulus of the specimen prior to drying (Dechow and Huynh, 1994).

Sites for bone sampling (Fig. 1) provided an overview of cortical bone material properties from throughout the inner and outer tables of the parietal bone. The 14 sites on each table included one at the parietal boss, eight near a bony suture, and five at (outer table) or adjacent to (inner table) the origin of the temporalis muscle.

To prevent possible infection, the investigator wore a mask, gloves, and a gown, and prepared bone specimens in a ventilation hood with a dental handpiece and a 5.0-mm trephine bur. Specimens were cooled continuously with a water drip during preparation. Prior to removal, bone specimens were marked with a graphite line parallel to the sagittal suture, indicating the specimen's orientation prior to removal.

After removal of each bone core, the diploë was split, leaving two cortical plates with attached trabecular structure (diploë). The diploë was removed by grinding with a Unimat 3 miniature lathe (Emco, Austria) under water irrigation. The specimens from both fresh and dry calvaria were stored in a solution of 95% ethanol and isotonic saline in equal proportions. This media maintained the elastic properties of the cortical bone over time with minimal change (Ashman et al., 1984; Dechow and Huynh, 1994). This storage medium also rehydrated the dry bone specimens prior to ultrasonic testing.

We measured the thickness, density, percentage ash weight, and elastic properties of each bone specimen. We measured specimen weight and differential volume in water and calculated apparent density based on Archimedes' principle of buoyancy (Ashman et al., 1984). Each specimen was measured at least twice to ensure consistency and to decrease measurement error. The technique used to harvest the bone specimens and test them ultrasoni-

cally is described elsewhere (Schwartz-Dabney and Dechow, in press).

We measured material properties with the pulse transmission technique described by Ashman et al. (1984) and Ashman and Van Buskirk (1987). The longitudinal ultrasonic waves generated by V323-SU piezoelectric transducers (Panametrics, Waltham, MA) resonated at 2.25 MHz. Longitudinal ultrasonic waves passed through the specimens in nine radial directions and the thickness of the bone cylinder. As on a clock face, we aligned the original graphite line, which was parallel with the sagittal suture at the time of bone core removal, in the direction of 12:00. Radial directions 1 and 9 served as an internal control, since they represented the same vector measured in opposite directions, and the ultrasonic velocities should be equal. The resulting time delay corresponded to the propagation of the wave through the thickness of the specimen, and it measured a phase shift of the signal before and after its transmission. Ultrasonic velocities were calculated, taking into account the time delay and the thickness of the specimen.

Results of the calculation in each of the nine radial directions determined the approximate orientation of maximum stiffness, as the wave traveled the fastest in that direction. The maximum velocity coincided with the stiffest direction of the bone or  $D_3$ . The least stiff direction was  $D_2$ . The velocity of the transverse waves was then measured in  $D_2$  and  $D_3$ , and in a direction  $45^\circ$  from each of them.

Relationships between the various velocities through the specimen and its material properties were derived from the principles of linear elastic wave theory based on Hooke's law (Ashman et al., 1984). We computed  $6 \times 6$  matrices of elastic coefficients, or "C" matrices from the time delays, and widths and densities of the bone specimens, and then calculated elastic moduli from the "C" matrices. The elastic constants quantify the relationship between a load (stress) placed on a structure and the resulting deformation of that structure (strain), within its elastic range (Cowin, 1989; Dechow et al., 1993). Calculated technical constants included: 1) Young's modulus, a measure of the ability of a structure to resist deformation in a given direction; 2) the shear modulus, a measure of the ability of a structure to resist shear stresses; and 3) Poisson's ratio, a measure of the ability of a structure to resist deformation perpendicular to that of the applied load.

Anisotropy was quantified in the plane of the cortical plate as a ratio,  $E_2/E_3$ , where  $E_2$  is the elastic modulus in the direction of minimum stiffness and  $E_3$  is the elastic modulus in the direction of maximum stiffness.

After the completion of ultrasonic testing, bone specimens were weighed and then dried at room temperature for 48 hr until the weights were constant. The bone specimens were ashed in a muffle oven (Neytronic 2202, Ney, Yucaipa, CA) at  $850^\circ\text{C}$  for 12 hr and weighed again. Ash weight percentage was calculated as the ratio of weight of each specimen post-ashing divided by the weight pre-ashing (Barengolts et al., 1993; Nordsletten et al., 1994).

Statistics were calculated for most data with the Minitab and SPSS statistical analysis programs. Differences between sites and between the inner and outer tables of the parietal bone were tested by repeated-measures ANOVA to account for the lack of independence between multiple specimens taken from a single individ-

ual (Zar, 1996). Specifically, we used a balanced, unrestricted ANOVA with a repeated-measures design and subject as the random factor to test for differences between individual skulls, tables, and sites in bone density, cortical thickness, ash weight, and elastic properties. For each of the sites, elastic properties along the axes of maximum and minimum stiffness in the plane of the cortical plate and perpendicular to this plane (through cortical thickness) were evaluated. The axis of maximum stiffness was always perpendicular to the axis of minimum stiffness.

Angular measurements of the orientation of the axis of maximum stiffness were analyzed with circular descriptive statistics, including the mean vector, circular standard deviation (S.D.), standard error, confidence intervals, and Rayleigh's test of uniformity (Zar, 1996) with the Oriana statistical analysis program. A generalized version of the Watson-Williams test determined differences between multiple circular means (Zar, 1996).

Because significant differences were found both between tables and between sites for two variables (thickness and ash weight), we tested whether the relationship between the inner and outer tables differed among sites by calculating a ratio of the inner table value divided by the outer table value for each bone specimen. Nonparametric tests (a mood median test and a Kruskal-Wallis test) evaluated differences between sites. We also calculated correlation coefficients and generated plots to examine correlations between the inner and outer tables for all variables.

## RESULTS

Thickness was significantly different among sites and tables (Table 1 and Fig. 2). The outer table was thickest along the sagittal suture and temporal line, and thinnest along the squamosal suture. In contrast, the inner table was thickest posteriorly and inferiorly. In both tables, the thinnest cortical bone was near the intersection of the coronal and squamosal sutures (site 12).

Overall, the outer table was significantly thicker than the inner table. The ratio of the thickness of the inner table to that of the outer table (mean = 0.94, S.D. = 0.21) showed no significant differences among sites. However, the large S.D. (0.21) and range (0.54–1.74) indicated that this pattern is highly variable. For all specimens, approximately one-third had an inner table of equal or greater thickness as the outer table. Thicknesses of the inner and outer tables were minimally correlated ( $R = 0.28$ ,  $P < 0.003$ ).

Percent ash weights had significant differences between sites and tables (Table 1, Fig. 3) ranging in the inner table from 51% at site 6 to 62% at site 13, and in the outer table from 51% at site 4 to 58% at site 13. Percent ash weights (%) were larger inferiorly and posteriorly on the inner table, and inferiorly and anteriorly on the outer table. The ratio of inner table to outer table percent ash weight showed no significant differences between sites. The average of all specimens (mean = 1.04, S.D. = 0.13, range = 0.82–1.54) suggested that overall the inner table was slightly more mineralized than the outer table, but not consistently so at any individual site. The correlation ( $R = 0.67$ ,  $P < 0.001$ ) between percent ash weight for the inner and outer tables was the largest for any variable. There was also a moderate overall correlation between ash weight (%) and density of  $R = 0.31$ ,  $P < 0.001$ , which was

**TABLE 1. Cortical thickness and ash weight percentage**

Site	Thickness (mm)				Ash weight %			
	Outer table		Inner table		Outer table		Inner table	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1.9	0.3	1.7	0.3	53	7	52	12
2	1.8	0.3	1.6	0.2	55	4	55	5
3	1.8	0.3	1.8	0.2	53	8	54	7
4	1.9	0.3	1.6	0.3	51	9	55	8
5	1.8	0.3	1.5	0.3	52	8	56	4
6	1.8	0.3	1.7	0.3	52	10	51	6
7	2.0	0.3	1.7	0.3	53	8	55	4
8	1.8	0.2	1.7	0.2	54	9	58	4
9	1.9	0.4	1.7	0.3	52	6	56	5
10	1.9	0.3	1.7	0.2	53	10	54	7
11	2.0	0.2	1.7	0.2	55	5	57	6
12	1.4	0.2	1.4	0.2	50	12	53	8
13	1.6	0.3	1.9	0.6	58	11	62	8
14	1.7	0.3	1.7	0.3	56	10	59	8
Grand mean	1.8	0.3	1.7	0.3	53	8	55	7
Anova	F		P		F		P	
Site	2.6		0.003		2.7		0.002	
Table	20.8		0.001		7.8		0.006	

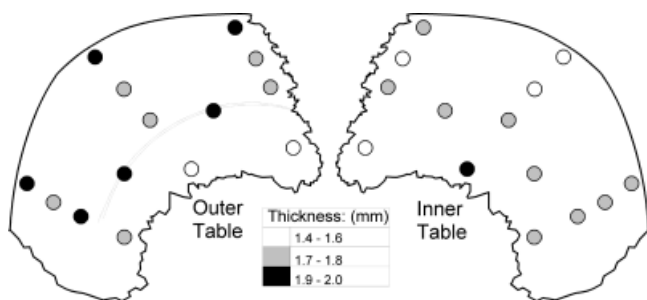


Fig. 2. Average thicknesses in mm.

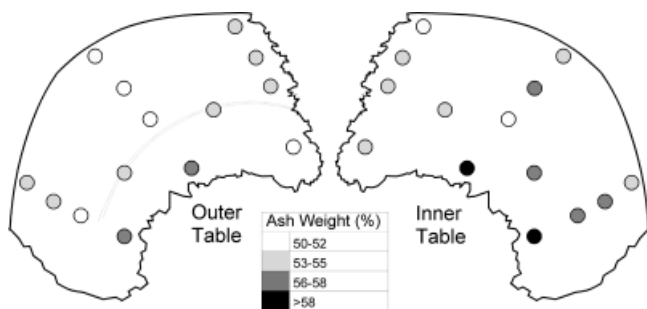


Fig. 3. Ash weight percentages.

larger for the outer table ( $R = 0.41$ ,  $P < 0.001$ ), and smaller ( $R = 0.20$ ,  $P < 0.05$ ) for the inner table.

Densities were significantly different between tables (Table 2), but not between sites. Ranges of densities were similar among tables (outer table: 1,496–2,064 mg/cm<sup>3</sup>; inner table: 1,495–2,065 mg/cm<sup>3</sup>), although the grand mean for the outer table (1,869 mg/cm<sup>3</sup>) was greater than that of the inner table (1,813 mg/cm<sup>3</sup>). Densities of the

**TABLE 2. Densities in mg/cm<sup>3</sup>**

Table	Mean	SD
Outer	1869	104
Inner	1813	127
ANOVA	F	P
Site	0.8	NS
Table	24.3	0.001

inner and outer tables were moderately correlated ( $R = 0.44$ ,  $P < 0.001$ ).

Elastic moduli differed significantly by direction ( $E_1$ ,  $E_2$ , and  $E_3$ ) ( $F = 404.8$ ;  $P < 0.001$ ). For each direction, there was a significant difference between tables, but not sites. Elastic moduli were significantly smaller for the inner table.  $E_1$  was the lowest (Table 3) with grand means of 10.6 GPa (inner table) and 13.0 GPa (outer table).  $E_2$  averaged 12.8 GPa (inner table) and 14.6 GPa (outer table). The largest values were found for  $E_3$ , averaging 18.1 GPa (inner table) to 21.0 GPa (outer table). None of the three elastic moduli were significantly correlated between tables.

Shear moduli demonstrated significant differences by direction ( $F = 472.1$ ;  $P < 0.001$ ). Like elastic moduli, shear moduli in each direction did not show significant differences between sites, but there were significant differences between tables. Shear moduli were lower on the inner table (Table 4), and, like elastic moduli, were not significantly correlated between tables.

Poisson's ratios differed significantly between directions ( $F = 198.8$ ;  $P < 0.001$ ) (Table 5). Poisson's ratios were largest in the  $V_{21}$  direction and smallest in the  $V_{23}$  direction. Other directions had intermediate values. Few significant differences resulted between sites and tables.  $V_{13}$ ,  $V_{21}$ , and  $V_{31}$  had differences between sites, while  $V_{31}$  had significant differences between tables.

The Rayleigh's tests for uniformity demonstrated significant mean directions of greatest stiffness at only 14% of

**TABLE 3. Elastic moduli in GPa**

Table	$E_1$		$E_2$		$E_3$	
	Mean	SD	Mean	SD	Mean	SD
Outer	13.0	1.9	14.6	2.9	21.0	3.8
Inner	10.6	2.2	12.8	3.2	18.1	3.8
ANOVA	F	P	F	P	F	P
Site	1.1	NS	0.6	NS	0.8	NS
Table	119.7	0.001	25.8	0.001	41.0	0.001

**TABLE 4. Shear moduli in GPa**

Table	$G_{12}$		$G_{31}$		$G_{23}$	
	Mean	SD	Mean	SD	Mean	SD
Outer	4.4	0.8	5.0	0.8	6.8	0.9
Inner	3.6	0.8	3.9	0.9	5.9	1.0
ANOVA	F	P	F	P	F	P
Site	1.3	NS	0.9	NS	0.8	NS
Table	111.4	0.001	119.1	0.001	68.3	0.001

**TABLE 5. Poisson's ratios**

Table	$V_{12}$		$V_{13}$		$V_{21}$		$V_{23}$		$V_{31}$		$V_{32}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Outer	0.45	0.13	0.20	0.09	0.48	0.10	0.19	0.08	0.30	0.10	0.26	0.09
Inner	0.42	0.17	0.21	0.08	0.47	0.09	0.19	0.08	0.34	0.14	0.27	0.10
ANOVA	F	P	F	P	F	P	F	P	F	P	F	P
Site	1.7	NS	2.0	0.022	2.2	0.009	1.7	NS	2.0	0.026	0.8	NS
Table	2.8	NS	119.1	NS	0.1	NS	0.3	NS	11.9	0.001	0.2	NS

sites (4/28), including sites 5 and 14 on the inner table and sites 4 and 8 on the outer table (Table 6, Fig. 4).

$E_2/E_3$  had significant differences between sites ( $F = 1.8$ ,  $P < 0.05$ ) but not between tables (Table 7, Fig. 5). Sites 10 and 11 on the inner table showed the least anisotropy, with mean values of 0.83 (S.D. = 0.10) and 0.81 (S.D. = 0.20), while site 12 showed the greatest anisotropy (outer table: 0.53, S.D. = 0.19; inner table: 0.57, S.D. = 0.16). Mean ratios at the remaining sites varied between 0.62 (site 5, outer table) and 0.77 (site 11, outer table). This range is small compared to the size of the S.D.'s, which varied between 0.08 (site 2, outer table) and 0.24 (site 9, inner table). A scatterplot of  $E_2$  and  $E_3$  for all specimens (Fig. 6) shows a moderate correlation ( $R = 0.47$ ,  $P < 0.001$ ) and the dispersion of the anisotropy ratios.

## DISCUSSION

### Material Properties

**Orientation of material axes.** The results demonstrate that determination of material orientation in cranial vault cortical bone is essential prior to measurement of elastic properties. A previous study in our laboratory (Dechow et al., 1993) showed a significant difference between the elastic properties of cortical bone taken from the superior orbit compared to the buccal surface of the inferior border of the mandibular corpus. The mandibular cortical bone is stiffer and denser, and has a consistent anisotropy in the plane of the cortical plate. Conversely, the aggregate

**TABLE 6. Direction of the axes of greatest stiffness in degrees**

Table	Site	Mean	SD	P
Inner	5	121.02°	28.4°	0.02
	14	47.12°	30.8°	0.04
Outer	4	121.07°	29.9°	0.03
	8	75.18°	24.7°	0.01

P values are based on Rayleigh's test of uniformity, which indicates the sites that have a significant mean orientation.

moduli for the supraorbital cortex indicate isotropy in this plane. However, that study (Dechow et al., 1993) did not determine the principal directions of cortical stiffness prior to measurement of ultrasonic velocities. Rather, it was assumed that the principal direction of stiffness of the mandible is parallel to the inferior border, and that of the superior orbit is parallel to the orientation of the browridges. This direction is near the actual average for the mandibular site (Schwartz-Dabney and Dechow, in press). However, the current results call into question the findings in the supraorbital region, as most sites in the parietal bone do not have significantly consistent orientations of the axis of maximum stiffness, and suggest that measurements based on anatomical orientation in the cranial vault are likely to be incorrect. At the least, the question of material orientation in the browridge region must be resolved before the accuracy of the measurements reported earlier can be determined.



Fig. 4. Orientations of the axes of maximum stiffness. Only four sites show significant mean orientations. The sites with asterisks are significant on the inner table but not on the outer table. The sites with bolded circles are significant on the outer table but not on the inner table. All shaded sites have no significant average orientations on either table. The bold intersecting lines indicate the mean orientations and the nonbold lines are the 95% confidence intervals.

TABLE 7. Anisotropy (ratio of  $E_2/E_3$ )

Site	Outer table		Inner table	
	Mean	SD	Mean	SD
1	0.73	0.15	0.74	0.14
2	0.76	0.08	0.68	0.15
3	0.76	0.11	0.68	0.14
4	0.73	0.13	0.75	0.21
5	0.62	0.10	0.66	0.22
6	0.64	0.20	0.76	0.13
7	0.75	0.16	0.67	0.12
8	0.76	0.15	0.74	0.17
9	0.75	0.11	0.71	0.24
10	0.73	0.17	0.83	0.10
11	0.77	0.11	0.81	0.20
12	0.53	0.19	0.57	0.16
13	0.67	0.20	0.69	0.21
14	0.69	0.16	0.73	0.18
Grand mean	0.71	0.15	0.72	0.17
ANOVA	F		P	
Site	1.8		0.05	
Table	0.4		NS	

Results from Evans and Lissner (1957) exhibited a similar problem. They measured ultimate compressive stresses in small specimens of embalmed parietal bone in two fixed orientations relative to the sagittal suture. Their average results suggested that near isotropy as compressive stresses in the direction of the suture are about 10% less than those at right angles to the suture. Our results showed an average  $E_2/E_3$  anisotropy ratio of 0.71 for all sites. We expect that compressive stresses in two perpen-

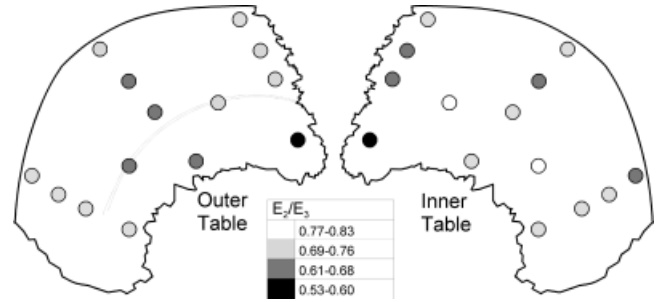


Fig. 5.  $E_2/E_3$  anisotropies.

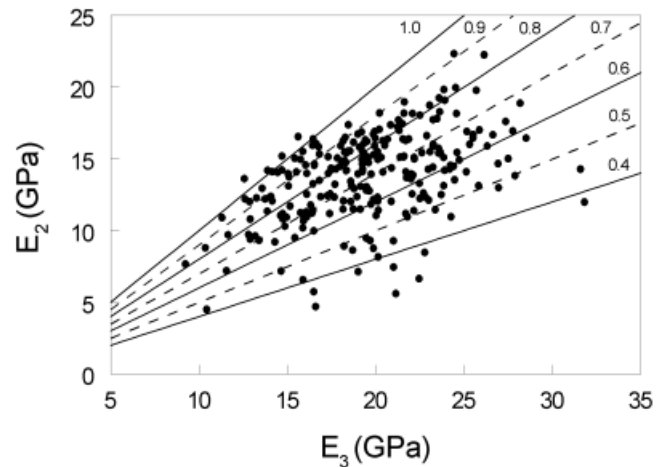


Fig. 6. Scatterplot of  $E_2$  vs.  $E_3$  showing the range of anisotropy values for all specimens. The ascending solid and dashed lines show the amount of anisotropy as indicated by the numbers next to the lines in the upper right corner.  $E_2$  is the elastic modulus in the direction of minimum stiffness, and  $E_3$  is the elastic modulus in the direction of maximum stiffness. There is a modest significant relationship ( $R = 0.47$ ,  $P < 0.001$ ) showing that as  $E_3$  increases in stiffness so does  $E_2$ .

dicular directions would also show greater differences if they were actually aligned with the principal axes of stiffness.

**Anisotropy.** Despite the lack of a consistent orientation of the axis of maximum stiffness at most sites in the parietal bone, average anisotropies were similar to those found in other parts of the skeleton (Table 8). Average anisotropies of parietal cortical elastic properties resemble those from the diaphyses of long bones (Yoon and Katz, 1976; Ashman, 1989; Rho, 1996). Relative values of elastic moduli illustrate an order ( $E_3 > E_2 \geq E_1$  and  $G_{32} > G_{31} \geq G_{12}$ ) that indicates transverse isotropy. This pattern contrasts with the average pattern in the mandible, in which  $E_2$  has relatively greater values than  $E_1$ . The similarity in anisotropies suggests the hypothesis that parietal cortical bone basically has a microstructure similar to that of cortical bone from the diaphyses of long bones, but the relative lack of strain results in random variation of material orientation.

**Densities and ash weights.** Our study showed different outcomes for two variables—ash weights and den-

**TABLE 8. Averaged values for elastic properties in GPa in three bones**

	$E_1$	$E_2$	$E_3$	$G_{12}$	$G_{31}$	$G_{23}$
Parietal	11.8	13.7	19.6	4.0	4.5	6.4
Mandible <sup>a</sup>	12.7	17.9	22.8	5.0	5.5	7.4
Tibia <sup>b</sup>	11.6	12.2	19.9	4.0	5.0	5.4

<sup>a</sup>Schwartz-Dabney and Dechow, in press.

<sup>b</sup>Ashman (1982).

sities—which are often assumed to measure similar aspects of cortical bone structure (An et al., 2000). It is likely that these differences relate to unique aspects of each measure. Ash weight is a measure of bone mineral content (BMC) (% mineral weight of dry bone weight), while density relates to bone mineral density (BMD) (wet weight divided by specimen volume in  $\text{g}/\text{cm}^3$ ). BMC varies with the degree of mineralization, i.e., mineral crystal size, content, and packing, while BMD is dependent on total bone volume, including porosity. The low overall correlation between ash weight and density ( $R = 0.31$ ) probably reflects this difference and also the relative similarity (low variance) between all sites in the parietal bone density measurements. The significant differences in ash weights between sites may reflect differences in bone mineral. According to Boskey (2001), not all bone mineral is the same; it varies in composition and crystal size according to bone, site, and physiological aspects, such as the remodeling rate. The lack of differences in density suggests homogeneity in bone porosity, i.e., variation in and among sites is similar.

Information on cranial bone densities in the literature is in agreement with our findings. Kingsmill and Boyde (1999) reported that the calvarial mean mineralization density is significantly lower than that of the mandible, yet it is higher than that of the femoral neck, fourth lumbar vertebral body, or iliac crest. Behiri and Bonfield (1984) found that human cortical bone fracture toughness increases with a relatively small increase in density. This is important considering the role that the cranial vault plays in protection of the brain, and the finding that the cranial vault is denser than some postcranial bones. A comparison of our current findings to previous work on the human mandible in our laboratory (Dechow et al., 1993; Schwartz-Dabney and Dechow, in press) shows that parietal cortical bone is on average less dense than that of the mandible. However, density in the mandible varies by region and density in the parietal bone is greater than in the least-dense regions of the mandible, such as at the symphysis.

Our percentages of ash weights for the parietal bone are similar to those obtained in other studies of fetal, growing, and adult human cranial vault bone. Kriewall et al. (1981) reported that the ash content of fetal cranial bone increases significantly from 50% to 68% with increasing gestational age of the subjects from 25 to 40 weeks. The ash content of the 6-year-old subject in Kriewall et al.'s study falls within the range of adult ash content reported by Curry (1969) (63–68%). Our mean values by site were slightly lower, ranging from 51% to 62%.

A unique aspect of our study is the determination of significant differences between the inner and outer tables, in which the outer table is on average denser but has a

lower average ash weight percentage than the inner table. This difference was found at 10 of the 14 sites. The greater average mineralization of the inner table may reflect a slightly lower remodeling rate. If, as suggested by Herring and Teng (2000), the ectocranial surface of the cranial vault (outer table) is under tension during biting and the endocranial surface (inner table) is under compression, then the difference in mineralization correlates with that found in artiodactyl and perissodactyl calcanei by Skedros et al. (1997). In these bones, remodeling in the compression cortex occurs at a slower rate than remodeling in the tension cortex. On the other hand, the lower densities in the inner table would typically be associated with more resorption spaces and a higher remodeling rate, but this association seems unlikely given the higher mineralization. In any case, the differences between the inner and outer tables are absolutely small, and if these differences are physiologically meaningful, their causative effects may be subtle.

**Thickness.** Most studies in the literature report full cranial vault thickness, with no attention paid to the thickness of the cortical plates. These studies showed that thickness is stable after maturity is reached (Tallgren, 1974). However, genetic influences on cranial vault thickness are low, as suggested by studies on pigs and armadillos, as cranial vault thickness increases more rapidly in juveniles with exercise than in genetically matched controls (Lieberman, 1996). During aging, systemic and functional factors are likely important, as thinning of the parietal bone is bilateral and symmetrical. Meschan (1974) discussed how this thinning phenomenon is usually related to lack of development of the diploë, with the inner table thickness being less affected than the outer table.

Cortical bone in the parietal is on average thinner than in the mandible (Schwartz-Dabney and Dechow, in press). Like the mandible, there are significant differences in thickness among parietal sites, but the thicknesses of these sites are equal to the lower range of mandibular cortical thicknesses. These differences are similar to those between the mandible and supraorbit, and may reflect lesser functional loadings in the cranial vault (Dechow et al., 1993).

### Elastic Properties

Our study showed no differences in elastic moduli between sites, unlike the mandible (Schwartz-Dabney and Dechow, in press).  $E_2$ ,  $E_3$ , and all shear moduli are larger in the mandible, indicating greater stiffness, similar to the contrast between the mandible and the supraorbit (Dechow et al., 1993). The exception was  $E_1$ , which was similar between the parietal bone and the mandible. This similarity was reflected in Poisson's ratios, wherein  $V_{12}$  and  $V_{21}$  were higher in the parietal bone.

The lack of differences in elastic and shear moduli between sites indicates that the stiffness of muscle-bearing bone may be similar to non-muscle-bearing bone. However, tests on specimens that come from muscle-bearing sites throughout the cranial vault, and exclude data from the inner table might be more revealing on this point. Our finding of no difference in cortical elastic moduli between sites differs from the few published studies that tested the full thickness or structural stiffness of the cranial vault bone. Schröder et al. (1977) examined full-thickness elastic moduli ( $D_1$  direction) at four sites and found that the

parietal bone is stiffer laterally. Barber et al. (1970), using a crush technique to measure the compressibility of 243 specimens from one cranium, found that the anterior cranial vault is stiffer than the posterior, but did not point out any specific differences within the parietal.

Wood (1971) measured differences between the three layers of cranial bone (inner table, diploë, and outer table), and the results conflict with those of the current investigation, in which we found no significant differences in elastic modulus between layers. The disparate results may be due to the fact that Wood used a different research technique than we did. Wood (1971) loaded the bone to failure in tension, and Z-axis modulation measured with strain gages determined the strain rate. We used an ultrasonic testing technique to derive the results without breaking the bone specimen.

### Functional Considerations

Although this work focuses specifically on the cortical material properties of the parietal bone, the results may be relevant to other diploic bones of the cranium including the occipital and frontal bones. Bosma (1986) described the extent of diploic cranial bone in humans as reaching anteriorly to the margins of the orbits and the base of the external nose, posteriorly to the margin of the neck, and laterally to the orifice of the external acoustic meatus and the conchal chamber of the external ear. The diploë diminishes toward the inferior portion of the temporal bone near the auditory meatus circumferentially and at the temporal region of the frontal bone lateral to the upper and posterior frontal bone.

The thickness of the cranial vault and its unique diploic construction, in which two sheets of cortical bone sandwich the more compressible diploë, are important functional features in protection of the brain from trauma (Meschan, 1974). According to Akkas (1975), the functional significance of this diploic structure is well illustrated when the cranial vault is modeled as a fluid-filled, three-layer spherical sandwich shell. This type of structure is a strong barrier protecting the brain, in which the diploë acts similar to a compressible cushion. Other investigators have explored similar concepts, such as Hubbard's (1971) layered beam model of the cranium, and Goldsmith's (1972) ideas regarding the ability of the diploë to reduce the weight of the skull without proportionately reducing its strength. None of these studies considered specific features of the structure of the outer and inner tables of cortical bone. Understanding these cortical plates functionally requires investigation into the differences in their immediate environments in addition to their role as part of the structure of diploic bone.

On the outer table, low functional strains (Picq and Hylander, 1989; Hylander et al., 1991; Ravosa, 1991; Ravosa et al., 2000) suggest that the cranial vault is overbuilt for absorbing muscular and masticatory loads (Meschan, 1974; Akkas, 1975; Kingsmill and Boyde, 1999). Yet the outer table tends to be thicker, denser, and stiffer than the inner table. Perhaps this is because the outer table is oriented to the external environment and directly bears muscular loads, while pressures on the inner table result from lesser intracerebral pressures transmitted through the dural coverings of the brain. It is also important to consider that the concept of an overbuilt cranial structure excludes information on bone strain in muscle attachment

sites, since no such data are available, and the parietal bone has extensive regions of muscle attachment.

If direct muscular loading is an important determinant of structure in the outer table, we might expect to see differences in material properties between muscle attachment sites and regions free of muscle attachment, but our investigation showed no such differences. However, local differences in parietal cortical bone loading resulting from the presence or absence of muscle attachment are not clear. Tensile strains across the sagittal suture in macaques during isotonic temporalis contraction (Behrents et al., 1978) suggest that the outer table is loaded during biting. However, at least during growth prior to sutural fusion, tension at the sagittal suture would have a dampening effect on parietal bone strain above the temporalis attachment, as strains in the sagittal suture of pigs are much larger than those in the adjacent bone (Herring and Teng, 2000).

Overall, variations in the mechanical properties of the human parietal bone suggest the effects of function but cannot be explained by current knowledge. An understanding of these variations requires further information on microstructure, mechanisms of growth and remodeling, and regional differences in the functional environment of the cranial vault and elsewhere in the skeleton.

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