Int. J. Morphol.,
27(2):553-564, 2009.

Relationship of the Parietal Foramen and Complexity of the Human Sagittal Suture

Relación del Foramen Parietal y la Complejidad de la Sutura Sagital Humana

Robert W. Mann; Jiro Manabe & John E. Byrd

MANN, R. W.; MANABE, J. & BYRD, J. E. Relationship of the parietal foramen and complexity of the human sagittal suture. ***Int. J. Morphol., 27(2)***:553-564, 2009.

SUMMARY: The purpose of this paper is to report on the relationship between the parietal foramen and complexity of the human sagittal suture. Examination of 110 Japanese human skulls (males=67, females=43) with at least one parietal foramen revealed that the sagittal suture in the area of the Obelion was the simplest portion (i.e., fewest interdigitations and shortest length) of the suture (paired t-test, P<0.0005), when compared to the outstretched suture length of three established sections: 1. Parietal foramen section (P); 2. Anterior to section P (B); and 3. Posterior to section P (L). Sutural complexity was also compared between individuals with unilateral foramen (n=48) and bilateral foramina (n=62) to see if there was a statistically significant difference. The results revealed a slight difference in section P (ANOVA Bonferroni, P<0.05), denoting that the sagittal suture at the Obelion in individuals with unilateral parietal foramen is more complex than in individuals with bilateral foramina. While no difference in sex was noted, this simplicity in part likely reflects redirected bone stresses around a circular opening resulting in reduced tensile stresses and increased compressive stresses adjacent to the parietal foramen. This phenomenon warrants additional research and has implications for bone biomechanics and development of the cranial sutures.

KEY WORDS: Sagittal suture; Complexity; Parietal foramen; Age.

INTRODUCTION

Study of the human cranial sutures has focused on such diverse topics as fractal analysis (Hartwig 1991; Yu *et al.,* 2003; Skrzat & Walocha, 2003a, 2003b, 2004; Gorski & Skrzat, 2006), indicators of age (Parsons & Box, 1905; Todd & Lyon, 1924, 1925a,b,c; Retzlaff *et al*., 1979; Baker, 1984; Meindl & Lovejoy, 1985; Lynnerup & Jacobsen, 2003), frequency and location of accessory ossicles (Berry & Berry, 1967; El-Najjar & Dawson, 1977; Sanchez-Lara *et al*., 2007), cranial dimensions (Skrzat *et al*., 2004) and sutural complexity as indicators of bone stresses (Anton *et al.*, 1992; Kanisius & Luke, 1994; Nicolay & Vaders, 2006). Few studies or reports, however, have focused on the frequency, location and variation of parietal foramina, and even fewer on the possible relationship between parietal foramina and complexity of the human sagittal suture (Topinard, 1878; Currarino, 1976). Although the biomechanical explanation for this causal relationship is outside the scope of this study, the present work reveals both a visual and statistically significant relationship between the complexity of the sagittal suture and proximity of the parietal foramen. The authors hypothesize that the parietal foramen, a normally occurring feature in human skulls, acts to alter and redirect compressive and tensile stresses resulting in a relatively simple suture.

Development of parietal bone. The parietal bone develops from a single intramembranous center near the eminence, beginning in the eighth fetal week and radiates outward in a sunburst pattern (Hoheisel, 1930; Currarino; Fazekas & Kosa, 1978 cited in Steele & Bramblett, 1988). The four sides of this approximately square shaped bone, which forms the sides and roof of the skull, join the frontal bone anteriorly along the coronal suture, the temporal and sphenoid bones inferiorly at the squamosal suture, the occipital bone posteriorly along the lambdoidal suture, and the opposing parietal bone superiorly at the sagittal suture (Gray, 1910). The concave endocranial surface of the two parietal bones contains deep grooves for the meningeal vessels, a shallow sulcus along the midline for the superior sagittal sinus, several

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cluster-shaped depressions and pits resembling clusters of grapes for the arachnoid granulations.

Slowed or delayed ossification in the posterior one-third of the parietal bone at the Obelion results in a slit or v-shaped notch, sometimes referred to as the subsagittal suture of Pozzi (Breathnach, 1965), fonticuius obelicus (Pernkopf, 1963), pars obelica (Scheuer & Black, 2004), or sagittal or third fontanelle, that widens the sagittal suture at that level (Currarino). Obelion, so named for its resemblance to the Greek symbol obelos ÷ refers to that portion of the sagittal suture between the parietal foramina; the dots of obelos represent the parietal foramina (Jamieson, 1937). Ossification and closure of the third fontanelle, which usually occurs in the fifth fetal month, often results in vestiges and normal anatomical variants known as obeliac bones, enlarged parietal foramina, parietal fissure, and one or more parietal foramina (Currarino). The role of the parietal foramen, other than transmitting an emissary vein or artery to the superior sagittal sinus, is still under investigation but may simply be the result of delayed or incomplete ossification as just described (Wu *et al*., 2000). In addition, when a parietal foramen is unusually large as the result of slowed ossification, the area around the foramen may be thinner and flatter (Boyd, 1930).

Simplification of the sagittal suture near the parietal foramen, a condition occasionally reported in the clinical, anatomical and anthropological literature (Topinard; Currarino; Hauser & DeStefano, 1989; Scheuer & Black), therefore, could be explained by slowed or delayed ossification. Koskinen *et al*. (1976), in contrast, suggest that rapid growth of the parietal bone would result in an increase in interdigitations and an overlapping of the suture. If this feature prevails as a uniform type, the complexity of the sagittal suture near the parietal foramen results in excess bone development, and the prematurely fusing suture with abnormal fibroblast growth factor (FGF) might lead to precocious osteogenic differentiation and craniofacial malformation (Sarkar *et al.*, 2001; Moore *et al*., 2002). Thus, ossification of the parietal bone might be one of the crucial variables in understanding the basic pattern of the sagittal suture and its simplicity near the parietal foramen.

Vault suture morphology, whether complex or simple, is a feature that physical anthropologists and others sometimes use as an indicator of ancestry when examining human skeletal remains. For example, highly complex sutures are often viewed as a Mongoloid (Asian) trait and simple sutures as Caucasoid (White) or Negroid (Black) (Rhine, 1990; Burns, 1999; Byers, 2008). The degree of suture complexity and its relationship to ancestry, therefore, has a medicolegal significance and may play a role in establishing the identity of unknown remains.

Although subject to a host of variables and not necessarily an accurate indicator of age (Hershkovitz *et al*., 1997), fusion of the vault sutures (Todd & Lyon, 1924, 1925a, b, c; Meindel & Lovejoy) and maxillary sutures (Mann *et al.,* 1987, 1991) has often been used as a method to estimate age at death. For example, Persson *et al*. (1978) advocated that the fusion of sutures is related to vascular, hormonal, genetic and biomechanical factors and the Obelion is believed to be the first region of the sagittal suture to begin closure (Topinard; Currarino). The present authors were unable to find additional information or research explaining why the sagittal suture starts to close at the Obelion first, despite suture closure being quite variable in individuals. Closure of the sagittal suture involves three fontanelles: 1. the anterior fontanelle located where the frontal bone and parietal bones meet, 2. the posterior fontanelle where the occipital and parietal bones meet, and 3. the third or sagittal fontanelle which is present in 50-80% of perinatal skulls, leading to the formation of one or more parietal foramina postnatally. The third fontanelle usually closes within the first two years postnatally (96% of cases) (Scheuer & Black). The timing of bony union and closure of this fontanelle might be related to complexity and morphology of the sagittal suture.

The reported frequency of the parietal foramen varies from 50 to 80% of individuals in different population groups (Scott, 1893; Boyd; Wysocki *et al*., 2006; Yoshioka *et al*., 2006) and has been shown to vary little in its number, location, size, and shape. As for position, the parietal foramen is reported as being located in the posterior one-fifth (Topinard) or one-third of the parietal bone; in other words, its location is approximately 2cm anterior to the Lambda in newborns and 2-5cm anterior in adults (Currarino), or an average distance of 83mm from the Inion (Yoshioka *et al*.).

The size of the parietal foramen has been reported as between 1.8-2.0mm (Wysocki *et al*.; Yoshioka *et al*.), although Boyd stated that the average is under 0.5mm and a size greater than 1.5 mm is rare. Unexpectedly, Wysocki *et al.* found that the average size of parietal foramina in Polish females was twice as large as in males (3.0mm in females and 1.5mm in males), ranging from 0.38-16.8mm, suggesting sexual dimorphism in parietal ossification. Boyd however, found no difference in age or sex. Circular, oval, or slit-like enlarged parietal foramina measuring several centimeters in diameter or length, however, have been reported in the literature (O'Rahilly & Twohig, 1952; Mann, 1990; Keats, 1992).

MATERIAL AND METHOD

Statistical analysis was conducted to test if the simpler form (i.e., complexity) of the sagittal suture anterior and posterior to the parietal foramen was consistent. The sample of skulls with an open or visible sagittal suture consisted of 79 Japanese males and 58 Japanese females (n=137) selected from the skeletal collection at the School of Medicine, Chiba University and the University Museum, the University of Tokyo in Japan (Fig. 1). A piece of clear plastic was taped over the outer surface of the skull and a black Sharpie® Ultra Fine permanent marking pen was used to trace the length of the sagittal suture and mark the location of one or more parietal foramina. These records served as the basis for further measurement.

To determine if the suture is less complex (i.e., fewest interdigitations and shortest length) in the area of the parietal foramina, samples with one or more parietal foramina were selected and the number of foramina in the left and right parietal bones noted. Skulls with a relatively complex sagittal suture were visually examined to determine if there was any morphological difference beyond the suture in those with one or more parietal foramina compared to skulls without foramina (closed or absent).

For each sagittal suture, a straight line was drawn from Bregma to Lambda. Next, three sections of equal length (15mm long each) were established as follows: (P) = centered on Obelion; (B) = anterior to section (P) and Obelion; and (L) = posterior to section (P) and Obelion (Fig. 2). This process was performed by manually annotating a photocopied image, which was then scanned at a high resolution and saved in TIF format. The digitally saved image was then opened with the software ImageJ, offered by the National Institutes of Health (NIH) and available at: http://rsb.info.nih.gov/ij/ (Rasband, 1997-2000), and the "outstretched" suture length of the three sections was measured. Measurement was taken along the suture lines, to include lines along ossicles or other isolated suture lines. Where the suture was interrupted, no measurement was taken. Thus, obliterated lines made no contribution to the data. Each outstretched suture in the three sections P, B, and L was measured to compare the complexity among the three sections and to see if there is any difference between the sexes.

To test the hypothesis that the sagittal suture is simplest (i.e. shortest outstretched length) at or around the parietal foramen, the authors compared the outstretched suture length of the three sections, B, P, and L and computed the frequency at which each section was simplest on each skull. Furthermore, the mean value of the combined sections B and L (described: section [B+L], calculated as: mean value = [section B + section L]/2), was compared with section P in order to assess if the suture around parietal foramen is least complex than its adjacent anterior and posterior portion. It must be noted that suture obliteration was observed more frequently in section P (13 instances of an interruption in the suture line), but the combination of sections B and L exhibited a similar number of instances of interruption (11 instances). A paired t-test examined any statistically significant difference in the outstretched length between section P and section B+L, and the eta squared statistic was used to reveal how large the difference was. This was followed by an ANOVA which tested the null hypothesis that there were no significant differences among the three sections. The ANOVA was followed up with pairwise comparisons of the three sections utilizing the Bonferoni criterion for significance. A correlation analysis utilizing Spearman's rho was performed to investigate the strength of relationship between lengths of the sections.

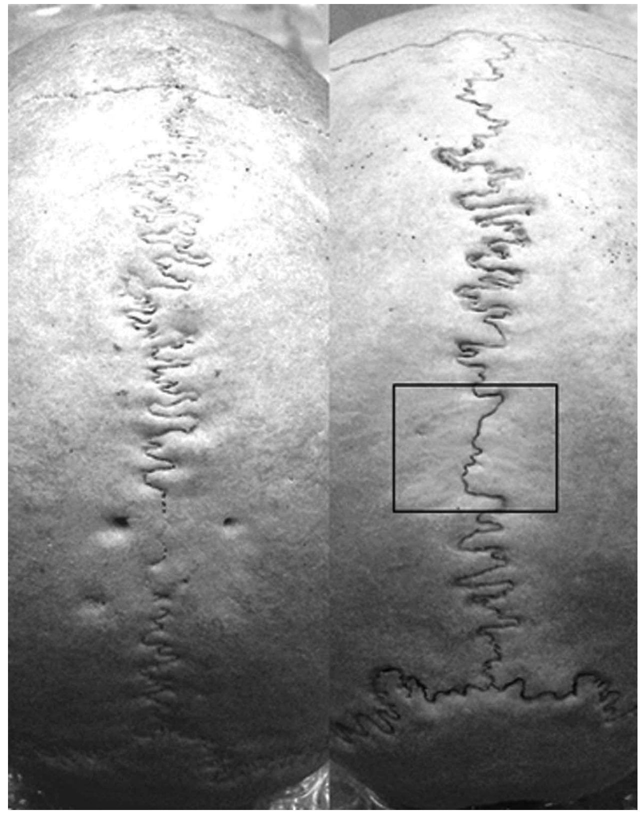


Fig. 1. Sagittal suture with bilateral parietal foramina (left). The suture was traced and the location of the foramina was recorded on the plastic overlay. Sagittal suture without parietal foramen (right). Despite the absence of a parietal foramen, the suture is simplest in the area (the Obelion) where one or more parietal foramina are usually located (square).

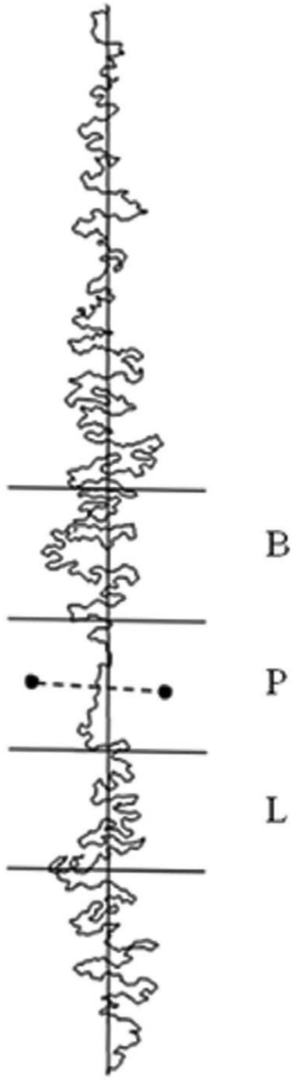


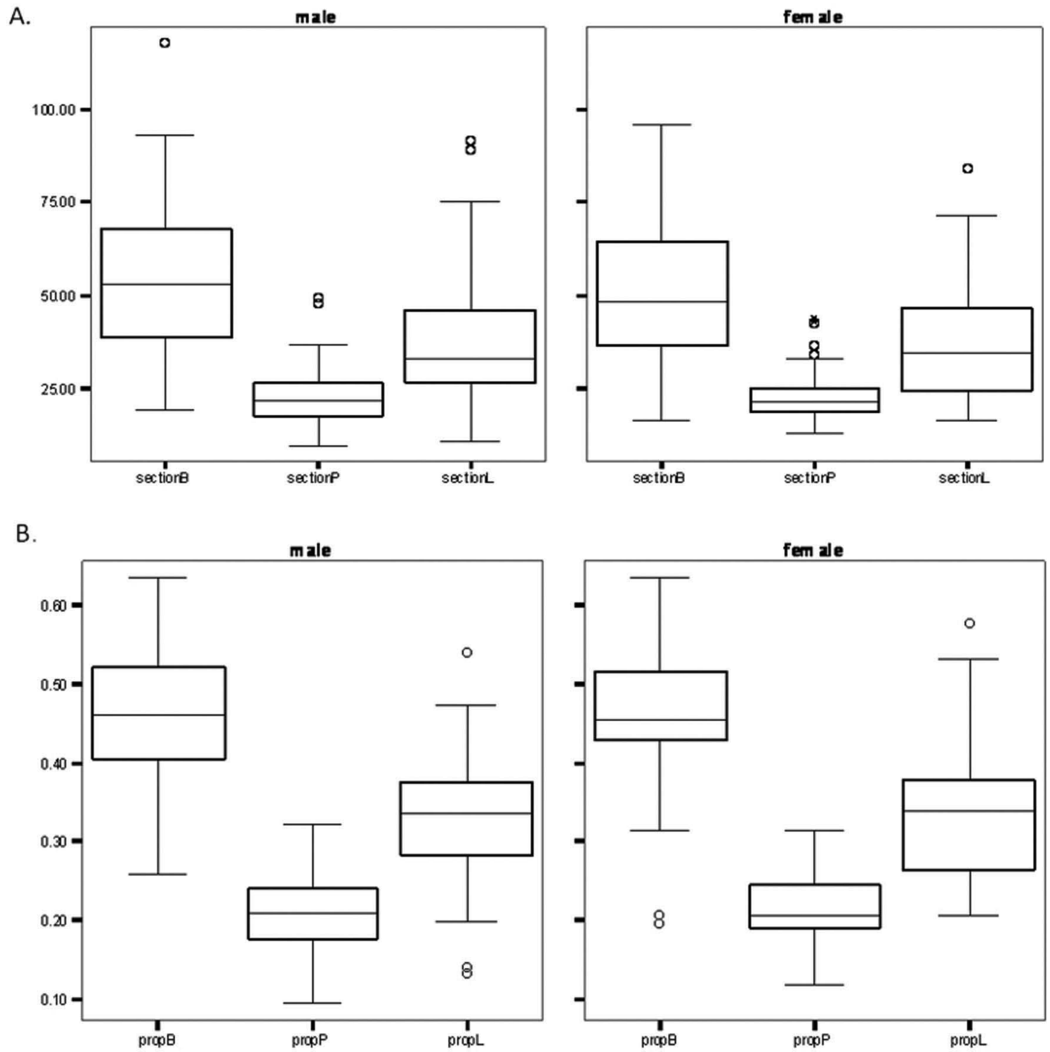
Fig. 2. Method for measuring suture complexity between the section at the parietal foramen (P) and the anterior (B), and posterior (L) sections. Each section measures 15mm in length. First, a line is drawn between Bregma and Lambda, then a 15mm section nearest the parietal foramen is set (if the foramina are located bilaterally, a middle point between the anterior and posterior levels of the foramina becomes the halfway point of the section. The anterior (B) and posterior (L) sections are obtained after the position of the parietal foramen (P) is established.

These tests were followed by an ANOVA and a Generalized Linear Model test to determine if the presence of multiple foramina affects the complexity of the suture in the vicinity of Obelion. First, a comparison of the complexity of the raw total length of section P between individuals with unilateral and bilateral foramina was made and examined (note: individuals without foramen were excluded due to technical difficulty). Second, rather than use the raw total length of section P, the proportion of the three sections accountable to P was used as follows: propP = P/(B+P+L). Another variable, "foramen" indicated whether the cranium had one or two foramina. The third variable included in the model was "complexity", which was calculated as the total sagittal suture length (following the actual contour) divided by the parietal chord. Complexity was included in the model to account for any sampling error in reference to the overall complexity exhibited by the suture. The GLM model was: propP = foramen * complexity, and the Type III sum of squares were used as the basis for the F tests. Statistical calculations were done in SPSS 15.0.

RESULTS

Sixty-seven (85%) of 79 male Japanese skulls and 43 of 58 (74%) Japanese female skulls possessed foramina (see Table I). This result is similar to what other scientists have reported (50-80%; c.f. Boyd; Scott; Wysocki *et al.*; Yoshioka *et al.*). The location of the parietal foramen was investigated utilizing skulls with one or more foramina. The curved distance from the Lambda to the foramen was measured, which resulted in an average distance and range of 3.8cm and 2-5cm, respectively. Exceptions to this average were found in two skulls where foramina exceeded 2-3mm above 5cm, giving a frequency distribution of: 2-2.5cm (4.6%), 2.6-3cm (4%), 3.1-3.5cm (17.3%), 3.6-4cm (34.6%), 4.1-4.5cm (32.6%), and more than 4.6cm (6.6%). Although some skulls did not exhibit a foramen, there appeared to be a portion of least complexity occurring 2-5cm anterior to the Lambda, where the parietal foramen likely would have been located (the Obelion) (Fig. 1).

Our results, just as reported by Currarino, indicate that the suture was simplest at the level nearest to the parietal foramen in the majority of individuals, rendering the section P the least complex of the three sections (see Fig. 3A, 3B and 4). Of 67 male skulls with one or more parietal foramina, section P was the least complex among the three sections in 60 (or 89%) of individuals. Section P was least complex in 38 (88%) of 43 female skulls. The average suture length of section P was similar in males and females (21.7mm and 21.3mm). Of all the sections, B was the most complex section (average suture length, 53.0mm in males and 48.1mm in females) followed by section L (average suture length, 33.3mm in males and 34.6mm in females) (Fig. 3A and 4). Figure 3B shows proportional comparison for each section and reveals that each section is more likely segregated.



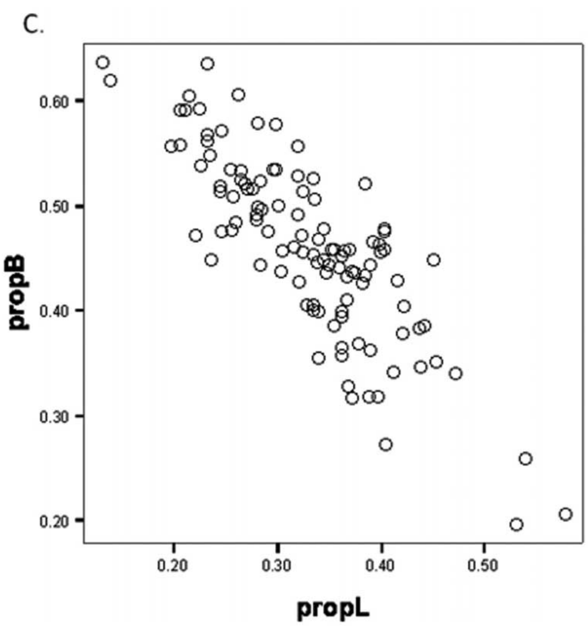


Fig. 3. A (top): Length of suture in each section: B, P and L (from left) Unit is mm. B (middle): Proportion of the sections of B, P and L (from left). Unit is percentage (value (%) = section length divided by total length of the three sections). C (bottom): Correlation between proportion of section B and proportion of section L. Of 67 male skulls with one or more parietal foramina, section P in 60 individuals (89%) was the least complex among three sections in the following order: P, L, and B, and 38 (88%) of 43 female skulls; the average suture length of section P in males was 21.7mm and 21.3mm in females. Of all these sections, section B was the most complex section (average suture length, 53.0mm in males and 48.1mm in females) followed by section L (average suture length, 33.3mm in males and 34.6mm in females).

Table I. Frequency of parietal foramen in the sample.

Sex (n)	Foramen On Suture (n/%)	Unilateral Foramen Left (n/%)	Unilateral Foramen Right (n/%)	Bilateral Foramina (n/%)	No Foramen (n/%)
Male (79)	0/0	12/15	16/20	39/49	12/15
Female (58)	1/2	9/15	10/17	23/39	15/25

Table II. Comparison of complexity between section P and its anterior and posterior sections.

Section	N	Mean (mm)	S D	T-test (P to B+L)	
				t	*P*
P	110	23.131	7.238	-17.159	<0.001
B & L	110	45.508	16.151		

Section P was compared with the mean of sections B and L (as B +L / 2). T-test reveals a significant difference between section P and the other two sections.

Table III. Complexity of the three sections of the sagittal suture in the vicinity of Obelion.

Section	N	Minimum (mm)	Maximum (mm)	Mean (mm)	S D
B	110	16.54	117.81	53.08	20.80
P	110	10.18	49.22	23.13	7.24
L	110	10.85	91.45	37.93	16.45
Source	**Sum of Squares**	**d.f.**	**Mean Square**	***F***	***P***
Between groups	49348.63	2	24674.31	97.95	0.000
Within groups	82376.54	327	251.92		
Total	131725.16	329			

ANOVA that tests the null hypothesis that there are no differences in the complexity of the three sections of the sagittal suture in the vicinity of the Obelion. All pairwise comparisons indicated significant difference at the 0.05 level using the Bonferroni criterion.

Table IV. Suture complexity difference at section P between individuals with unilateral and bilateral foramina.

A

Parietal Foramen	N	Mean (mm)	S D	One-way ANOVA	
				F	*P*
Unilateral	48	24.671	8.213	3.959	<0.05
Bilateral	62	21.939	6.191		

B

Source	Type III Sum of Squares	d.f.	Mean Square	*F*	*P*
Corrected Model	0.064	2	0.032	19.430	0.000
Intercept	0.685	1	0.685	416.951	0.000
Foramen	0.001	1	0.001	0.418	**0.519**
Complexity	0.063	1	0.063	38.547	0.000
Error	0.166	101	0.002		
Total	4.847	104			

A (top): Suture complexity comparing the raw total length of section P between individuals with unilateral and bilateral foramina. B (bottom): The model tested was: propP = foramen * complexity, and was intended to provide a basis for evaluating the effects of multiple foramina while controlling for the effect of the overall complexity of the suture. Variable propP was calculated as P / (P+B+L). Complexity was calculated as the total sagittal suture length divided by the parietal chord. Simple statistics with an F-test are given in A and GLM test results in B.

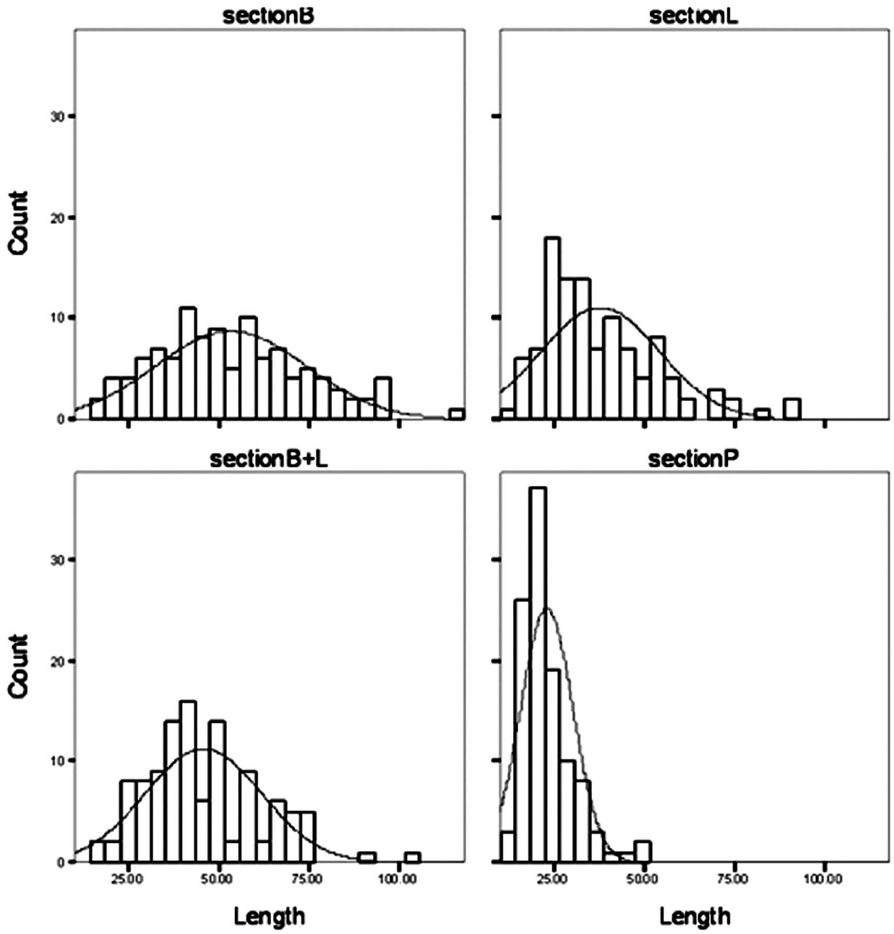


Fig. 4. Distribution of each sectional outstretched suture length. "Section B+L" is the mean value: value=(section B + section L)/2. Notably, length of section P is clustered around 25mm.

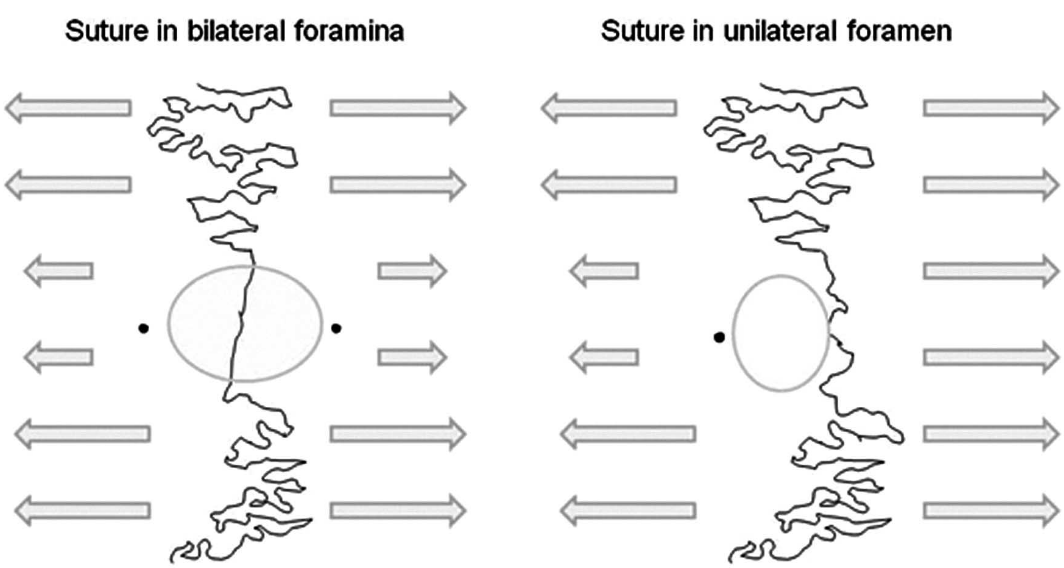


Fig. 5. Diagram of possible tensile activity (arrows) in relation to sutural complexity with parietal foramen/ foramina. Shaded circle reveals a possible area of reduced tensile stresses.

Using the total sample of 110 skulls, a paired t-test was conducted to examine if there was a statistically significant difference in sectional length between section P and section B+L (mean value), without discriminating by sex. The results indicate that there is a significant difference between section P and section B+L (paired t-test, t=-17.159, P<0.0005) (Table II). Eta squared was also computed in this regard and reveals relatively larger effect (0.73). The ANOVA test found that the three sections are significantly different (F=97.947, P<0.0001) and all are different from one another at the P<0.0001 level (Table III). The order of complexity from most to least complex was: B, L and P.

A relatively high correlation was seen in proportion B (value = length of B/total length of the three sections) versus proportion L [Spearman's rho, r=-0.79, n=110, P<0.0005] (Fig. 3C), and there was no significant correlation between proportion P and other two sections. This finding might reflect that suture complexity shares a certain pattern between section B and section L, while there was no correlation with section P because it was consistently less complex, regardless of the complexity of section B and/or L.

Exceptions to these findings were found in the skulls of seven males and five females. Two males and one female showed relatively consistent complexity throughout the parietal chord; however, section P proved to be more complex than sections B or L. This varying complexity might be the result of the rate of development of the parietal bone, combined with irregular or differing tensile and compressive stresses exerted by the temporalis muscle. Also, less complexity adjacent to Obelion was seen in three males and two females. In another two males and two females, section P was slightly longer because the suture was simple in both sections P and L. While the role of the musculature on sutural complexity is outside the scope of this study, the areas of the sagittal suture that lie closest to the parietal foramen are consistently simpler than those areas closer to Bregma and Lambda.

The suture samples grouped by unilateral foramen and bilateral foramina were compared utilizing the ANOVA and the GLM test. In the ANOVA comparing the total raw length of section P between these two groups, there was a significant difference (F=3.959, P<0.05), indicating that the sagittal suture in individuals with unilateral parietal foramen are slightly more complex in this section than individuals with bilateral foramina [unilateral (Mean=24.67(mm), SD=8.21), bilateral (Mean=21.93, SD=6.19)] (Table 4A). However, results in the GLM indicate that the number of foramina does not significantly affect the complexity of the suture (Table 4B).

DISCUSSION

Examination revealed that in 89.5% and 88.3% (males and females, respectively) of Japanese human skulls, the area of the sagittal suture closest to the parietal foramen was the least complex and shortest segment compared to the sections immediately anterior and posterior to the Obelion. The relative simplicity of the sagittal suture at the Obelion is likely the result of many variables, including redirected stresses associated with mastication and other physical activities, as well as its proximity to the lambdoidal suture and muscular activity associated with the nuchal crest. Perhaps not surprisingly, the sagittal suture at the Obelion in individuals with a unilateral foramen shows a slight tendency to be more complex than in individuals with bilateral foramina. Test results indicate, however, that this pattern could be a result of sampling error. Were the pattern real, this increased complexity in a unilateral trait versus a bilateral trait could possibly reflect increased tension in the former, resulting in greater complexity (Fig. 5).

Numerous animal studies, for example, have shown that the morphology of a suture is affected by biomechanical stresses associated with chewing and biting (Hubbard *et al.*, 1971; Behrents *et al.,* 1978; Smith & Hylander, 1985; Hylander *et al.*, 1991; Huang *et al.*, 1994; Herring & Teng, 2000; Markey *et al.*, 2006; Herring & Mucci, 2007 and Markey & Marshall, 2007), which results in a combination of tensile, compression and shear forces along different parts of the same suture. Alaqeel *et al.* (2006), for example, reported that mechanical forces and stresses associated with a variety of activities results in shear stresses of the frontal and parietal bones along the coronal suture, compressive forces in the parietal bones near the vertex, and tensile forces in the posterior portions of the parietal bones in the area of the parietal foramen. Generally speaking and in the words of Enlow (1990), sutures are "tension-adapted growth sites," such that tensile forces result in a widening of suture margins and bone development.

Experimental in *vivo* studies of animals, however, have provided contrasting results. Markey *et al.* (2006), for example, surgically implanted strain gauges into the sutures of fish (Polypterus endlicherii) to study the relationship between suture form and function during feeding. These researchers found that the interfrontal and frontoparietal sutures that are normally loaded in tension were less interdigitated in cross section than the interparietal suture that was simultaneously undergoing compression. Markey and colleagues found that interdigitated (complex) sutures resulted from compression and less interdigitated (less complex, simpler) sutures were associated with tension. Additional animal studies in fish (Markey & Marshall, 2007), pigs (Herring & Mucci, 1991; Herring & Teng, 2000), and goats (Jaslow & Biewener, 1995) reported similar findings, indicating that increased interdigitation is associated with compression and decreased interdigitation with tension.

Mechanical forces exerted, absorbed and redirected in the areas surrounding the parietal foramina might result in an increase in tensile forces in certain areas and a decrease in compressive forces in other areas of the parietal bone near the Lambda, resulting in reduced complexity along the sagittal suture. While perhaps not a true analogy, the circular opening in a rotunda designed architecturally to strengthen a structure, might reflect a similar condition in bone, such that the opening (foramen) alters or redirects the weight and stresses exerted on the structure. It is also possible that the presence of emissary vessels filling the parietal foramina alters the stresses in the area of the Obelion.

ACKNOWLEDGEMENTS

This research was supported in part by an appointment of the second author (Jiro Manabe) to the Postgraduate Research Participation Program at the Joint POW/MIA Accounting Command/Central Identification Laboratory (JPAC/CIL) administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and JPAC/CIL. We thank Dr Kazuhiro Sakaue at Department of Anthropology, National Museum of Nature and Science, Dr Yoshiharu Matsuno at School of Medicine, Chiba University and Dr Gen Suwa at the University Museum, the University of Tokyo for their cooperation.

MANN, R. W.; MANABE, J. & BYRD, J. E. Relación del foramen parietal y la complejidad de la sutura sagital humana. ***Int. J. Morphol., 27(2)***:553-564, 2009.

RESUMEN: El propósito de este trabajo es informar sobre la relación entre el foramen parietal y la complejidad de la sutura sagital en humanos. Se examinaron 110 cráneos humanos de individuos japoneses (hombres = 67, mujeres = 43) con al menos un foramen parietal, revelando que la sutura sagital en el área del obelion fue la parte más simple (es decir, menos interdigitaciones y menor longitud) de la sutura (vinculado la prueba t, p <0,0005). Cuando se comparó la extensión de la longitud de la sutura se establecieron tres secciones: 1. Sección foramen parietal (P); 2. Anterior a la sección P (B), y 3. Posterior a la sección P (L). La complejidad de la sutura también fue comparada entre los individuos con foramen unilateral (n = 48) y forámenes bilaterales (n = 62) para ver si había una diferencia estadísticamente significativa. Los resultados revelaron una ligera diferencia en la sección P (ANOVA Bonferroni, P <0,05), que indica que la sutura sagital a nivel del obelion en los individuos con foramen parietal unilateral es más compleja que en los individuos con forámenes bilaterales. Si bien no hubo diferencia según sexo, esta simplicidad en parte, probablemente refleja la redirección de las fuerzas del hueso alrededor de una abertura circular, lo que reduce la resistencia a la tracción y aumenta la fuerza de compresión adyacente al foramen parietal. Este fenómeno justifica la investigación adicional y tiene implicaciones para el desarrollo óseo y biomecánica de las suturas craneales.

PALABRAS CLAVE: Sutura sagital; Complejidad; Foramen parietal; Edad.

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Correspondence to:
Jiro Manabe
JPAC/Central Identification Laboratory
310 Worchester Ave. Hickam AFB
HI 96853-5530, USA.

Tel: 808-448-1768
Fax: 808-448 1982

Email: jiro.manabe@jpac.pacom.mil

Received: 15-04-2009
Accepted: 16-05-2009