Are There Any Regularities in Cranial Sutures?

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Summary: Fractal dimensions (D) were calculated for quantitative description of microscopic irregularities of suture-lines (sagittal, coronal, lamboid) in human cranial vaults. These suture-lines were found to be fractal curves with $1.2 < D < 1.5$. Fractal dimensions did not differ with kinds of suture-lines, ages and individuals. Thus, characteristics of wave forms between different kinds of suture-lines could not be shown with fractal dimensions.

Wavelengths were measured to analyze apparent macroscopic regularities in sagittal sutures. Wavelengths were found to differ with ages and three age stages were distinguished: growth, fusing and obliterating stages. In the growth stage, there were less differences in wavelengths between individuals than in other stages.

Sutures are junctions between irregular interlocking edges of certain contiguous skull bones in vertebrates, occupied by fibrous tissue. Observations with scanning electron microscope showed that bone margins become highly complex and irregular, developing spikes and processes which interlock with other so intimately that bones are difficult to separate even when denuded of all connective tissue (Prichard, Scott and Girgis; 1956, Markens and Oudhof; 1980). Oppenheim (1907) measured suture lengths and compared them between races, but apart from this, little that connected has been written on the suture pattern. We examined the suture pattern with the mathematical concept “fractal”, which is effective to deal with apparently irregular patterns in nature (Mandelbrot, 1982).

Fractal dimensions were calculated for criteria of irregularities.

On the other hand, macroscopic observations of sutures on ectocranial surfaces showed that suture-lines, lines marking junctions of edges of skull bones, looked like regular patterns. In a sagittal suture of a young Orangutan (Fig. 1), sizes of processes of adjacent bones were so constant that the suture-line could be regarded as a wave on a straight axis. Processes in posterior parts became larger in height than those in anterior parts. A coronal suture-line of an adult Orangutan (Fig. 1) seemed to lay on a locus of a circle. Sizes of processes from frontal bones were larger than those from parietal bones. These observations have led to the suggestion that macroscopic patterns of suture-lines might have some regularities.

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which were mechanically determined. Wavelengths were calculated for criteria of the regularity in sagittal sutures, which appeared to show the most regular pattern among sutures in the human cranium.

Materials

Twenty three Japanese skulls used in this study were a part of the collection of the Department of Anatomy, the University of Tokyo. Sexual differences were ignored due to limited number of specimens in each age group.

Specimens were divided into five age groups:

- 3 years old (5 exs.)
- 6-11 years old (3 exs.)
- 20 years old (5 exs.)
- 41-42 years old (5 exs.)
- 68-72 years old (5 exs.)

Methods

Preparations (Fig. 2)

Sutures (sagittal, coronal, lamboid) in cranial vaults were taken on video tapes with a microscopic color camera (ITC-350M, Ikegami Co., Tokyo), and suture-lines were traced on acetate papers placed on the monitor screen. In order to analyze suture-lines, traces were put, as digital images of 512x 480 pixels of 2 gray levels, into a microcomputer (PC-9801, NEC, Tokyo) through a video image processor (NEXUS 6400, NEXUS Co., Tokyo).

Fractal dimensions (Fig. 3)

Fractal dimensions in three kinds of suture-lines were calculated. Though there are several ways to obtain fractal dimensions (Takayasu, 1985), the following procedure (Morse, 1985) were used here.

Enclose the object in a square and divide it into squares of side r. Let N(r) be the number of squares the object enters and plot log N(r) against log r. Suppose that for values of r, the graph is almost linear with slope −D. Then the object is called as fractal
Fig. 3. Preparation for calculation of wavelength. a) Traces of cranial suture were b) put into a microcomputer through a image processor and converted to x and y coordinates \((x(1), \ldots, x(n); y(1), \ldots, y(n))\). c) y coordinate series were used to measure wavelength.

and D can be interpreted as the fractal dimension, since

\[
\log N(r) = -D \times \log r + \log K
\]

where K is a constant.

**Wavelengths** (Fig. 4)

Digital images of suture-lines were thinned to continuous series of pixels, which were again converted to x and y coordinates by the image processor. The wavelength of sagittal suture was defined as the average of distances from crest to crest. Positions of crests were obtained as points of inflection calculated from coordinate component series.

**Results**

**Fractal dimensions** (Fig. 5 A, B, C)

Suture-lines were found to be fractal and their fractal dimensions differed little with ages and individuals: 1.3—1.5 in sagittal sutures, 1.2—1.4 in coronal sutures, 1.3—1.5 in lamboid sutures.

**Wavelengths** (Fig. 5 D)

Distances measured along the straight axis between both ends of sagittal suture-lines were similar in five age groups (11 cm—14 cm). Wavelengths in the oldest age group
Fig. 4. Method for calculation of fractal dimension. a) Traces of suture-lines were placed under a grid. Number of squares entered by the suture-lines were counted.
b) The logarithm of the number of squares entered by the suture-lines was plotted against the logarithm of the number of squares along one side of the grid. Sizes of grid were varying from 1 to 80 pixels. The slope of the line equals the fractal dimension, D.

Fig. 5 Fractal dimension and wavelength.
Fractal dimensions of a) sagittal suture, b) coronal suture and c) lamboid suture differed little between ages and individuals. d) Wavelengths of sutura sagittalis were measured as the average distance from crest to crest and found to be differed with ages.
were larger than in the other age groups. In the youngest group, differences in wavelengths between individuals were markedly little.

Observations of wave forms (Fig. 2)

Three kinds of suture-lines had their own wave forms respectively. Sagittal suture-lines lay on a straight axis and three areas could be distinguished with the complexity. Wave forms of anterior and posterior parts were smooth and those of middle parts were rough.

In coronal sutures, the size of processes from frontal and parietal were almost the same in contrast to the case of Orangutan.

Wave forms in lamboid suture-lines were the most complex. Many sutural bones were observed to be intercalated in the central part of the suture. Wave forms in the lateral part looked like those of squamosal suture.

Discussions

Suture-lines are fractal patterns.

Three kinds of suture-lines in human cranial vaults were found to be fractal curves with $1.2 < D < 1.5$. The fractal dimension ($D$) could be used as a convenient quantitative description of a form of nature. Oppenheim (1907) described forms of suture-lines by “Index” which was the ratio between the length along the suture-line and the straight length between both ends of the line. When a suture-line was complex or overlapped with itself, the ratio could not be calculated. On the contrary, fractal dimensions of any suture-lines can be obtained.

The ranges of fractal dimensions differed little with kinds of suture-lines, ages and individuals (Fig. 5). Thus, the characteristic of wave form of each suture could not be shown by the fractal dimension. Comparative studies are necessary to know whether fractal dimensions are equivalent among mammals.

One of the possibilities of understanding forms of nature is to convert them into mathematical forms. Mandelbrot (1982) has claimed that coastlines were usually modeled in a first approximation by Koch curve (Fig. 7). Koch curve is one of famous fractal shapes and fractal dimensions of this curve is estimated as $\log 4 / \log 3 = 1.26$. The value is fallen in the range of fractal dimension of coastlines, rivers and suture-lines. In other words, the degree of complexity of suture-lines are equivalent for that of geographical features. The exact model of suture-lines has not been formulated, but the pattern of the suture-line seems to be similar to Koch curve.

Wavelengths of sagittal sutures change with ages

We stressed that shapes of suture-lines were complicated and irregular, but as shown in the sagittal suture of Orangutan (Fig. 1), there appeared to be some order in the form of suture-lines. Wavelengths were measured to examine the order. The wavelength defined here is not an established concept, but a practical definition of the wavelength applicable to biological materials.

It was shown in Fig. 6 that three stages could be definitely distinguished according to the differences in values of wavelength. In the oldest age group (70 years old), the increase of wavelengths was thought to be due to the decrease in the number of crests which in turn was due to obliteration of suture by ossification. This stage could be called as an obliteration stage. In the youngest age group (3 years old), there were little individual differences of wavelengths. Oppenheim (1907) also stated that middle part of sagittal sutures showed regular patterns from the second to the twelfth year after birth. In the way of bone growth and structure, the third year after birth is a
The construction begins with an "initiator", a straight line with a unit length. Then one pasters upon the midthird of the line a triangle with side of length \( a/3 \). The same process of addition of triangles is repeated with each side, and then again and again, ad infinitum.

Critical period. From at birth to this period, the growth of vault is achieved principally by acceration and absorption on their superficial and deep surface respectively. At birth, the cranial vault is unilaminar, the two tables and intervening diploe appearing around the fourth year (Sperber 1976). These findings led to the suggestion that suture-lines in 3-year-old age group in this study display patterns which are determined by expansion and ossification of bones of cranial vaults. Main function in this stage is assumed to be active bone growth. From 6 to 40 year-old age group, wavelengths differ little with ages and wave forms are similar. Main function of sutures in these stages is suggested to make the firm bond of union between neighboring bones. These stages can be assigned to fusing stage.

**Characteristics of wave forms**

Each kind of suture-lines showed its own wave form and composition (Fig. 2). Oppenheim (1907) divided sagittal sutures into four areas, which corresponded to three fontanells and one intermediate part. We could not find remains of fontanells and apparently distinguished three areas with the complexity of wave forms. The difference of complexity is suggested to be caused by mechanical factors such as traction exerted by temporal and other muscles and/or due to the developmental origin of connective tissues which occupied sutures: neural crest in anterior parts and mesenchym in middle and posterior parts (Douarin, 1982).

Sutures have been classified according to the form (serrata, squamosa and plana) or the developing origin (facial and vault; Prichard, 1956). The similarity of adjacent bones is also an important factor for classification and analysis of forms of suture-lines. When adjacent bones are equivalent, interlocking processes of sutures, such as nasal, frontal and sagittal sutures, become apparently symmetrical. On the contrary, the asymmetric suture pattern shows the different character of bones or hemisheres of the brain on both sides (i.e. coronal sutures). Quite different sizes of adjacent processes in a coronal suture of Orangutan (Fig. 1) suggest the presence of different role played by frontal and parietal in the formation of sutures. The size of processes in human coronal sutures are so similar (Fig. 2) that frontal and parietal are suggested to make a similar contribution to the formation of
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Sutural bones surrounded with irregular loops, were often found in lamboid suture. Further studies are necessary to make clear the origin of sutural bones.

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