VIA MEDICA

ORIGINAL ARTICLE

Vol. 62, No. 2, pp. 119–122

ISSN 0015–5659
www.fm.viamedica.pl

Fractal dimensions of the sagittal (interparietal) sutures in humans

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[Received 5 November 2002; Revised 27 January 2003; Accepted 27 January 2003]

Traditional studies of the cranial suture morphology have focused mostly on visual estimation and linear measurements, and thus on evaluating their complexity. This paper presents a new look on cranial sutures as curves, which can be analysed by fractal dimension. This new measure seems to be a much better method of expressing properties of sutural patterns than traditional methods. Our findings suggest that the fractal dimension of non-complicated interparietal sutures slightly exceeds the topological dimension of the line, that is 1.0, whereas the fractal dimension of complicated sutures may reach a value of 1.4 or even more. The difference between the minimum and maximum decimal fraction of the fractal dimension indicates a three-fold increase in complexity in the investigated sutures.

key words: sutural pattern, sutural complexity, morphometry

INTRODUCTION

Cranial sutures show morphological variations and different levels of interdigitation. Sutural pattern varies from the slightly convoluted curve to the complex labyrinthine one. Cranial sutures resemble curved and irregular lines that correspond to the opposing edges of the bones joined by a connective tissue. A magnified suture reveals details in the form of subtle concavities and spicules, sinusoid in shape. All these sutural meanders include similar but smaller curves and projections, which are repetitive in nature. Cranial sutures vary from simple wavy sutures to complex folded ones and moreover they may develop to the self-similar patterns. Thus the microarchitecture of the cranial suture suggests the fractal nature of its construction [8]. Euclidean geometry is not well equipped to describe biological structures while fractal geometry provides a tool for the description of irregular, rough, and fragmented structures. Traditional measures of sutural complexity are based on scoring their interdigitations [4, 14]. Hence, a sutural pattern as a curve can be described by fractal dimension, and its value would depend on cranial suture complexity. According to fractal theory, the length of a curve is equal to the product of the number of rulers needed to cover the curve, and the length of the ruler used. The length of a curve is therefore not a constant, but it is related to the ruler length, by a power-law. The double-log plot of number of rulers versus the length of the ruler is linear for a true fractal curve. The slope of this line characterises the scale-independent property of the fractal curve and the fractal dimension is a function of this slope [11].

The goal of this investigation was to present the possibility of using fractal dimension in estimating sutural complexity. Images of the sagittal (interparietal) sutures were used to test the computer-assisted method of counting fractal dimension on the basis of cranial suture images.

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MATERIAL AND METHODS

Estimation of the fractal dimension was performed on the images of the interparietal sutures of 25 human skulls. The selected areas of sutures were photographed and scanned with a flatbed scanner. The explored area of the suture was selected arbitrarily and it extended from bregma to vertex. This portion of the interparietal suture usually lies approximately in a horizontal plane. This position restricts any disturbances related to the projection of cranial silhouettes to the camera. The original digital images were processed to obtain silhouettes of the sutural patterns. A line 1 pixel thick presented each of the sutural silhouettes. On the basis of acquired digital images, fractal dimensions were estimated with a box-counting method using a computer-assisted procedure. The binary image of the sutural silhouettes was superimposed on a succession of square grids of increasing edge length (Fig. 1). The number of 'tiles' in the grid where the border contacts the silhouettes of cranial suture was counted. Then the logarithm of the number of tiles encountered was plotted against the logarithm of the tile edge length. A fractal dimension is equal to the slope of the plotted line and it may vary from 1.0 to 2.0. Usually it is a decimal fraction.

The value of fractal dimension is interpreted as follows. The whole number portion (the digit to the left of the decimal place) depicts the dimension of an object, while the decimal portion (the digit to the right of the decimal place) represents the level of complexity of the object. For example, if the fractal dimension equals 1.2, then 1 indicates the linear feature of an object, while 2 expresses the level of structural complexity related to the curvatures of the line. Greater values of a fractal dimension indicate a more complex structure while lower values denote a decrease in structural complexity. The range between minimum and maximum, standard deviation and the variance expressed the variability of the fractal dimension of the interparietal sutures in the investigated cranial collection.

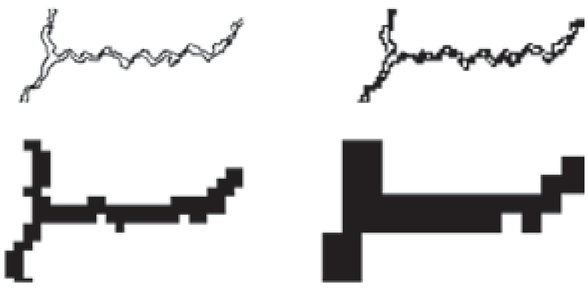

Figure 1. Initial steps of the binary image of the cranial suture superimposed with the tiles of the increasing edge.

RESULTS

The calculated value of fractal dimension of the selected portion of the interparietal suture exceeded the topological dimension (1.0) in most studied skulls. The mean value of fractal dimension of the investigated interparietal sutures was estimated as 1.34, with standard deviation equal 0.084 and variance 0.007. Fractal dimensions of the cranial sutures' images in the region of interest varied between 1.16 and 1.48. The range of variation of the estimated fractal dimension indicates a triple increase of sutures' complexity in the examined specimens, because the maximal value of the decimal fraction (48) is three-fold the minimal value (16) (Table 1).

External appearance of the interparietal suture became more complicated if fractal dimensions increased. Figures 2 and 3 show interparietal sutures

Table 1. Statistical data for the complexity of interparietal suture expressed by fractal dimension

Number of observations	Mean value	Minimum value	Maximum value	Std dev	Variance
25	1.34	1.16	1.48	0.084	0.007

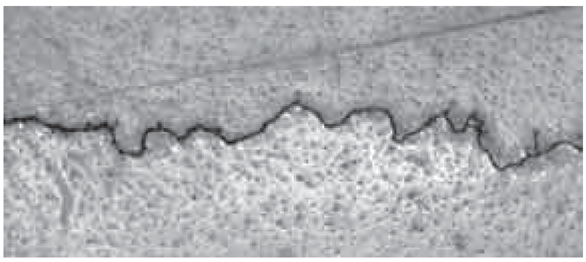

Figure 2. A segment of non-complicated, undulate interparietal suture, DF = 1.16.

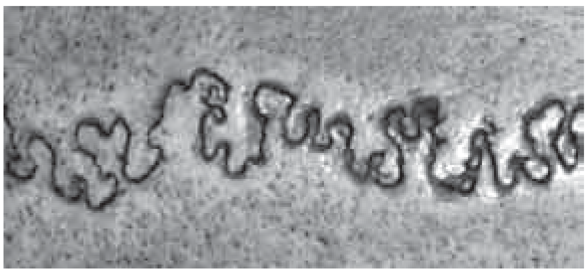

Figure 3. A segment of complicated, meandric interparietal suture, DF = 1.41.

characterised by different complexity and two distinct exocranial patterns — undulate and meandric.

As regards the fractal division of sutural complexity, linear or undulate sutures are non-complicated and their fractal dimension exceeds slightly the topological dimension of the line, that is 1.0. Increase of complexity of the exocranial alignment of the interparietal suture is combined with higher values of the fractal dimension, e.g. 1.30 or 1.40. This was observed frequently in the vertex of the skull that is contrary to the bregmatic part of the suture that shows lesser complexity.

DISCUSSION

Euclidean geometry describes silhouettes of cranial sutures as curved lines, whose topological dimensions equal 1, no matter how many folds there are or how extensive their roughness is. Therefore from the topological point of view a curved line and a straight line are indistinguishable. Parameters of Euclidean geometry cannot serve as proper descriptors of sutural morphology and they do not inform about complexity. Fractal dimension perceives the irregularities and coarseness of the studied object. Basing on fractal geometry in metrical analysis of cranial sutures, it is possible to estimate their complexity by using fractal dimension [8]. Traced silhouettes of the interparietal sutures yielded fractal dimension so they can be regarded as fractals. It means that the analysed cranial sutures show some degree of self-similarity, especially those of a high degree of irregularities. According to Long et al. [8] intricate interparietal sutures show 2–3 orders of self-similarity in a wavy line reflecting cranial suture. Results obtained in our study confirm this observation and suggest a high variation of interparietal suture complexity.

Knowledge about sutural complexity, its variation and relation to other cranial features seems to be important in analyses of craniofacial deformities [1]. A premature closure of the sagittal suture gives a scaphocephalic shape to calvaria, with abnormal basicranial morphology, providing evidence of the developmental relationship of neurocranium and basicranium [3, 13].

Sutures, as the sites of growth, play an important role during craniofacial development, especially during rapid expansion of the neurocranium [10].

Margins of cranial bones are joined by sutures, whose development is initiated during embryogenesis. Beginning from the earliest stages until the full development, sutures are composed of five layers passing from one bone to the edge of the other: the first cambial layer, the first fibrous capsule, the loose cellular middle layer, the second fibrous layer and the second cambial layer. Such a structure of the cranial sutures enables skull growth by apposition of osseous matrix along the edge of the sutures [2, 12].

Quantitative measure of sutural complexity may also be useful in considerations about mechanical properties of cranial sutures. As was stated by Jaslow, there is a relation between durability of cranial sutures and their complexity. There is proportional increase of sutural durability according to increase of cranial complexity [7]. Moss demonstrated that the interdigitation of sutural margins occurs in response to extrinsic forces, such as muscular activity [9]. The sutures not only provide the interstitial growth of the skull, but they also alter the transmission of stress and strain through the skull by means of fibres, which connect the bony edges [6]. It was found that if fusion of sutures does not occur at an early age, the quantity and quality of sutural interdigitations can indicate the presence and direction of stress [5].

Application of fractal dimension in the study of cranial suture morphology enables the quantitative evaluation of complexity of sutural patterns. Our study intended to demonstrate how the method of estimating fractal dimension could be applied to analysis of cranial suture complexity. Fractal dimension reflected sutural complexity, objectively therefore it seems to be a helpful parameter in morphological study, which does not have to be based only on descriptive terms.

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