Characterization of cerebral cortical folding in the developing infant brain

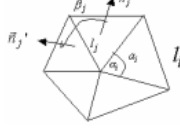H. Haidar[1], A. J. du Plessis[1], J. S. Soul[1]

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Introduction One of the most challenging problems in elucidating the factors governing the developing human brain is understanding the complex development of the gyral pattern of the cerebral cortex. From 20 to 40 weeks gestational age (GA) in particular, the human brain undergoes a remarkable transformation in terms of the development of complex gyri and sulci. The factors that influence the development of the gyral-sulcal pattern are likely both genetic and environmental. Premature birth and early acquired brain injury probably exert a significant effect on the development of this three-dimensional (3D) complex structure. Methods to elucidate this process of cortical development would greatly facilitate understanding of normal brain development as well as the impact of in utero and postnatal events on this process. The development of brain mapping techniques using 3D magnetic resonance imaging (MRI) offers the opportunity to understand better the development of the human cerebral cortex.

Recent studies have shown the importance of the mean curvature as a measure of cortical folding [1, 2]. Based on the calculation of this parameter, the cortex can be formally divided into gyri and sulci. The mean curvature is required to perform optimal gyral parcellation and subsequently to correlate these regional gyral parcels with regional brain function. Another frequently used measurement of cortical folding is the gyrification index (GI). However, as GI is a mean of two-dimensional measurements, GI depends on the slice orientation. Thus, any change of the head position in the scanner may affect the results.

To address the problem of cortical folding in newborns, we determined the mean curvature of the cerebral cortical surface of the developing infant brain. We also introduced a new measure to characterize the folding process. Thus, in addition to the mean curvature, this measure quantifies the cortical shape using differential geometry. We applied this technique to measure cortical folding in 3D brain MRI data obtained from premature newborns scanned serially from preterm age to one year postnatal age.

Methods The mean curvature can be determined, approximately, using different mathematical approaches. The most accurate method was introduced by Cachia et al [1]. We applied this mathematical approach to the cortical surface extracted from the tissue classification maps obtained using a post-processing pipeline of MR images [3]. A three dimensional mesh was created using an algorithm based on marching cubes. Smoothing was performed to decrease the noise in the triangular mesh. The mean curvature was then calculated in each vertex of the mesh from the areas of the surrounding facets (a_i), the lengths of the triangles bordres (l_i), the angles between the facets borders (α_i) and the angles between the normals to the facets (β_i) as shown below [1].

$$H = \frac{\frac{1}{4}\sum_j \beta_j l_j}{\frac{1}{2}\sum_i a_i - \frac{1}{8}\sum_i l_i^2 \cot(\alpha_i)}$$

(1)

Thereafter, sulci were defined as the areas with a negative value of mean curvature and gyri were selected as areas with a positive value of mean curvature. To characterize the folding process of the neonate cortex, we introduce a new measure of the cortical surface. We define the folding index (FI) as the ratio of the sulcal surface area (Ss) to the gyral surface area (Sg).

$$FI = Ss / Sg \qquad\qquad (2)$$

FI has the advantages, compared to GI, of being three-dimensional and thus independent of head position. Ss and Sg were determined as the summation of the areas of facets with either negative or positive mean curvature, respectively.

Results We applied our technique to measure mean curvature and the folding index in 15 infants born prematurely. Eight of them were scanned first within a few weeks after birth (gestational age GA= 27-35 weeks). Another scan was conducted at term age (GA = 40 weeks) and a third scan at one year of age, corrected for prematurity (80-96 weeks post-conceptional age). The other seven infants were scanned just at preterm (GA= 25-34 weeks) and and one year (88-112 weeks). All MRI scans were obtained using 1.5T scanner (GE Signa; GE Medical Systems, Milwaukee, Wis.). We acquired three-channel MRI on the whole brain of newborns. The channels represent dual echo images obtained with a conventional spin-echo imaging with voxel size 0.7x0.7x3 mm and SPGR (Spoiled Gradient Recalled acquisition in the steady state) with voxel dimensions of 0.7x0.7x1.5 mm, all obtained in the coronal plane.

The results showed a significant increase in mean mean curvature of the cortex from preterm to one year of age (p<0.001). FI also increased significantly from preterm to one year of age. FI varied between 0.30 and 0.45 at preterm age. At term, the FI values were between 0.33 and 0.456. At one year of age, FI ranged from 0.67 to 0.75. The increase of FI reflects the appearance of more gyri and sulci which directly characterize the folding process of the developing neocortex. There was a statistically significant difference in FI between data obtained at all three age groups by one way ANOVA and by pairwise comparisons within subgroups of infants (i.e., subgroups of infants with 2 vs. 3 scans, p<0.001 for all).

Conclusions To our knowledge, this is the first study to use the mean curvature as a serial measure of changes in cortical folding in premature infants. This study illustrates the potential of mean curvature to quantify the changes in shape that take place during cortical development. We believe that the novel measure presented in this work, folding index (FI), will be helpful for estimation of folding process, outlining the maturation pattern of the neocortex and quantifying changes in cortical folding that may result from early acquired brain injury.

References 1- A. Cachia et al.. A Mean Curvature Based Primal Sketch to Study the Cortical Folding Process from Antenatal to Adult Brain. In *Proc. 4th MICCAI*, pages 897--904, 2001.

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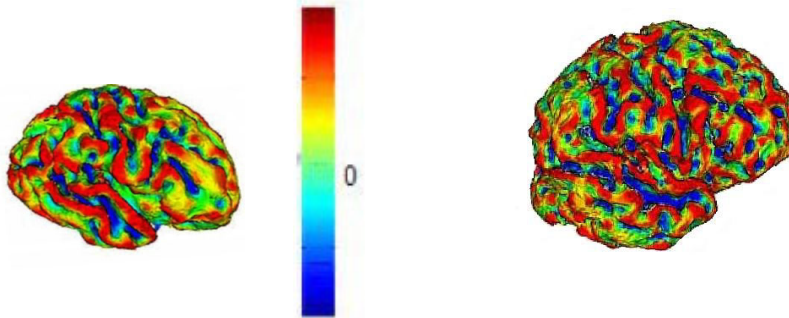
Fig.1. Maps of mean curvature: Scans at preterm (left) and one year of age (right). Blue (negative) areas correspond to sulci, while Red (positive) areas to gyri.