Growth patterns of the developing infant cerebellum using Laplace's equation

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Introduction Advanced post-processing techniques of three-dimensional magnetic resonance imaging (3D MRI) data are increasingly used to analyze structural changes related to acquired injury or disease, growth and development, and plasticity in the brain. One of the newest types of such analyses is the assessment of growth patterns of different structures of the human brain. This type of analysis is particularly suited to the evaluation of the human infant's brain in its period of dynamic growth and development. Such an approach may be extremely useful in studying the impact of premature birth and/or early acquired brain injury on the developing infant brain. Thompson et al. used four-dimensional quantitative maps of growth patterns of the brain of children aged 3-15 years to report a rostro-caudal wave of peak growth rates in the corpus callosum (1). In a recent study, Gogtay et al. showed the patterns of growth of human cortical gray matter development from a mean age of 9 to 16 years (2). Their results suggest that phylogenetically older brain areas mature earlier than newer ones. These studies were performed using continuum mechanical tensor maps, which represents a simulation based on the solution of huge system of second order partial differential equations. However, the solution of such a system is not trivial and represents a significant computational task. In this work, we present a simple and fast method to estimate the growth patterns of different anatomical structures of the human brain. Our method is based on the solution of the Laplace equation between time-points of growth. We demonstrate the application of our approach on the cerebellum of prematurely born infants.

Methods We aligned the segmented cerebella of different time points into a common coordinate system. This system consists of three planes perpendicular to each other that all pass through the junction of the superior and inferior medullary vela (at the apex of the fourth ventricle), which represents the origin. We considered the mid-plane passing between the two cerebellum hemispheres as the "ideal" sagittal plane. The 'ideal' axial plane was defined as the plane perpendicular to the "ideal" sagittal plane and passing through the horizontal white matter fiber tract that passes transversely through the origin. The "ideal" coronal plane was defined as the plane perpendicular to both "ideal" sagittal and axial planes, and passing through the origin. Once the cerebella are aligned in this system of coordinates, we solved the Laplace equation between the cerebella of two different time-points. For that, we set Dirichlet conditions on the boundaries with low potential on one time-point and high potential on the other. Laplace's equation can be written as:

$$\Delta u = 0 \qquad \text{(I)}$$

where u is the potential function. The solution of (I) provides a unique one-to-one mapping of each point on the surface of the cerebellum at the first time-point to the corresponding surface at the second time-point. We define the displacement due to the growth of each point on the boundary of the first time-point as the length of the path of streamlines formed by the gradient of the solution of this equation. Different algorithms are used to calculate such arclengths (3, 4). For visualization of the growth patterns over the group, we used standard conformal mapping techniques to average displacement maps of different cerebella for the entire group.

Results Six healthy prematurely born babies (gestational age at birth between 25 and 30 weeks) were scanned three times. The first scan was performed within a few weeks after birth ("preterm scan" at 28-36 weeks postconceptional age, PCA). The second scan was acquired at 40 weeks PCA ("term scan") and the third scan at one year of age (92-103 weeks PCA). 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 the infants. 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. An expert manually segmented the cerebellum on the SPGR channel. We applied our method to obtain four-dimensional quantitative maps of growth, i.e. displacement maps of the cerebella between preterm and term age, as well as between term and one year of age (see Figure 1). We also obtained average displacement maps for the period between preterm and term age (Figure 2a), and for the period between term and one year of age (Figure 2b). As demonstrated by these figures, the patterns of growth during these two periods were different. From preterm to term age, growth occurred predominantly in the posterior regions of the cerebellar hemispheres, while from term to one year of age, growth was more pronounced in the superior region of the cerebellar hemispheres.

Conclusions We presented a new method to estimate the growth patterns of anatomical structures of the developing human brain. Our method is based on solving the Laplace equation between two different time-points of a developing structure, in this case the cerebellum. We believe that this method will be essential to elucidate the normal maturation pattern of the infant brain and to quantify changes that result from premature birth or early acquired brain injury.

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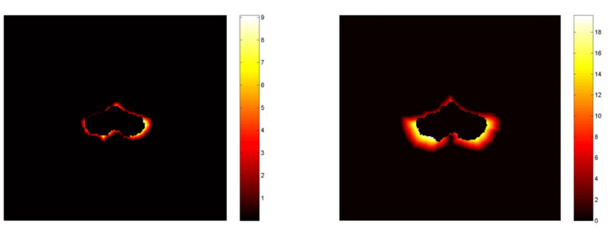
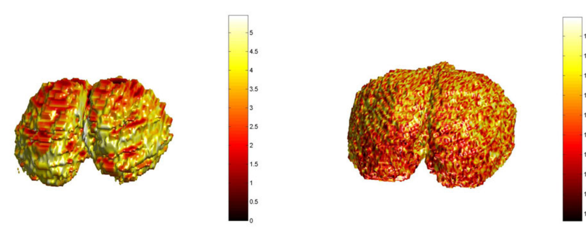


a) b)

Figure 1. 2D coronal view of the displacement maps in mm of the cerebellum of one infant from preterm to term age (a), and from term to one year of age (b). Note that the scales are different for the two displacement maps.



a) b)

Figure 2. 3D rendering of the average displacement map in mm of the cerebellum of a group of healthy premature infants from preterm to term age (a), and from term to one year of age (b). Note that the scales are different for the two displacement maps.

References

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