A PDE approach for automatic thickness estimation using partial volume classification

Easswar Balasubramaniam[1], Anand Joshi[1], David Shattuck[2], and Richard Leahy[1]

[1]*Electrical Engineering, University of Southern California, Los Angeles, CA, United States,* [2]*Neurology, University of California, Los Angeles, CA, United States*

Introduction: Cortical thickness variation is widely studied in a myriad of applications ranging from childhood development to studies of neurodegenerative diseases and detection of focal cortical dysplasia in epilepsy. Manual thickness measurement is tedious and difficult and can be inconsistent due to the highly convoluted geometry of the cerebral cortex. We propose a novel approach to solve this problem using an anisotropic form of Laplace's heat equation. We build on earlier work that uses isotropic heat propagation between inner and outer cortical surface, each held at a constant temperature, as a model for computing thickness [1]. By using Partial Volume Coefficients (PVCs) representing fractions of gray matter/white matter (GM/WM) or GM/cerebral spinal fluid (GM/CSF) to vary the speed of heat flow we can obtain more accurate thickness measures. We describe the method and examine differences between the proposed anisotropic method, the isotropic method, and the linked distance approach.

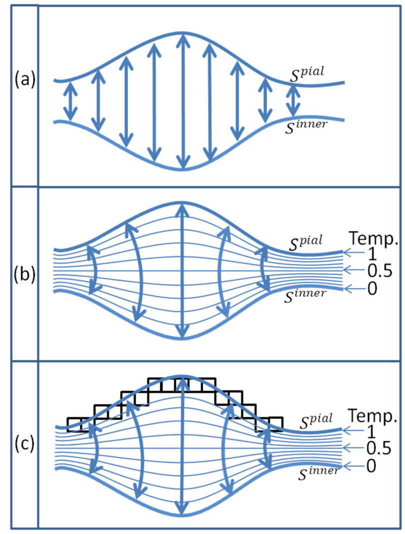

Figure1: (a) Linked Distance (b) Isotropic (c) Anisotropic ; (b) shows iso-contours of temperature and (c) shows larger temperature change in PVC voxels near S^{pial}

Method: A number of preprocessing steps were performed on the raw MR images to identify the inner and outer boundaries of cerebral cortex and to compute PVCs representing GM/WM and GM/CSF fractions for voxels within and surrounding these surfaces using BrainSuite (http://brainsuiteorg) [2]. The MR volume and associated partial volume map was then upsampled to 512x512x512 (~.5mm) voxels using linear interpolation. This volume was segregated into three regions including two fields of constant temperature: the inner field (WM, ventricles, subcortical nuclei), having a value of 0 and the outer field (CSF, skull and scalp), having a value of 1. Separating these two regions is the cortex through which heat is transferred at a rate determined by the PVCs from the inner surface, S^{inner} to the outer, S^{pial}. Rate of heat transfer is determined by the PVCs such that pure gray matter regions have constant speed while GM/CSF and GM/WM partial voxels have a speed inversely proportional to the fractional content of GM in the voxels, ($PVC_x = [\,\%\, content\ of\ GM\,]^{-1}$). The distribution within cortex is computed by minimizing the energy in the gradient of the harmonic field (∇f). To find the thickness we compute the surface S^{mid} representing the isosurface at which the temperature is 0.5. Cortical thickness is then computed as the inverse of the outward gradient of the temperature field on S^{mid}.

Isotropic	Anisotropic
$\min_u \int \lVert\nabla f\rVert^2 d\vec{x}$ S.T. $u \cap S^{inner} = 1$ and $u \cap S^{pial} = 0$	$\min_u \int PVC_x \lVert\nabla f\rVert^2 d\vec{x}$ S.T. $u \cap S^{inner} = 1$ and $u \cap S^{pial} = 0$
$Thickness_{(s)}^{isotropic} = (\lVert\nabla f\rVert)^{-1}{}_{s \in S^{mid}}$	$Thickness_{(s)}^{anisotropic} = (\lVert\nabla f\rVert)^{-1}{}_{s \in S^{mid}}$

Results: Results for a single subject are shown in Figure 2.The thickness maps are shown together with their histograms for each of the three methods.

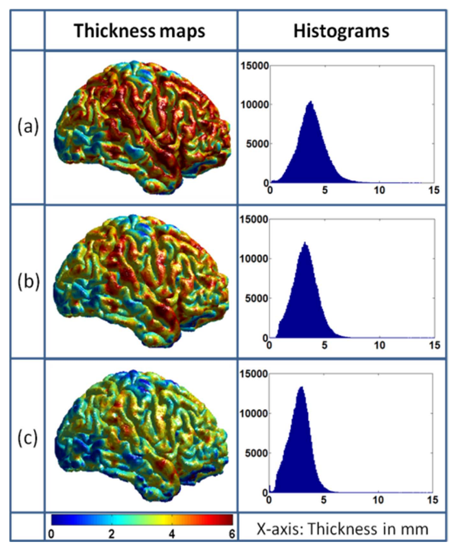

Figure 2: Cortical Thickness maps and Histograms for (a) Linked Distance (b) Isotropic (c) Anisotropic

Discussion: We have investigated three methods for computing cortical thickness. Linked distance between tessellated inner and outer surfaces is the fastest method, but results in average thicknesses that are slightly larger than the other two methods and direct measures reported in the literature. The isotropic method also shows slightly higher average thickness values than are reported in literature. The anisotropic heat flow method shows thickness values that are in line with the literature [1][3][4]. Furthermore, the upper tail of the histogram is shorter in this case, indicating very few locations with thicknesses in excess of 5mm. In general the thickness profiles are similar in all three cases, but the mean, standard deviation and tails of the histograms are notably different. Detailed evaluation and comparison of these methods is planned.

Conclusion: Of the three methods, the anisotropic method produces results that are closest to those reported by direct measurement [3]. However, this is a single example and further evaluation is needed to establish the accuracy and robustness of this approach relative to the alternatives. Incorporation of the anisotropy should produce not only improved thickness measures but also robustness to specification of the inner and outer boundaries provided that the partial volume fractions are accurate.

References:

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