Do cortical layers conform to the Laplace equation?

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Introduction:

Cortical profiling is an increasingly important tool in cortical parcellation and determination of cortical thickness [1]. Profiles traversing the cortex have often been constructed by assuming that the two surfaces of the grey matter are 'equipotentials' and numerically solving the Laplace equation to locate the intermediate contours and thus the orthogonal profiles. This Laplace approach [2] is more stable and robust than nearest distance or orthogonal projection methods [3]. Moreover the constructed profiles do not intersect, and they reach the cortical boundaries perpendicularly. It has also been surmised that these profiles are more realistic or "natural", i.e. running along cortical columns, since they appear to follow the cortical blood vessels [4]. The question studied here is: Can the Laplace equation solution adequately characterize the conformation of cortical layers and cortical columns, as defined by cytoarchitecture or myeloarchitecture? With ultra-high resolution MR imaging, we have been able to answer this fundamental question by comparing the Laplace solution with the clearly defined Bands of Baillarger. These are important myeloarchitectonic features known to parallel cytoarchitectonic layers 4 and 5b ([5], [6]) and can be readily observed in high resolution cadaver brain MRI [7].

Materials and methods:

Two formalin-fixed blocks of human post-mortem brain were scanned on a 7-T MR system (Siemens, Erlangen, Germany). FLASH sequences were used to obtain T2* weighted images of the pre- and postcentral gyrus (isotropic resolution of 70 µm, TE=13ms, TR= 50ms, Fig. 1) and of the occipital pole (isotropic resolution of 150 µm, TE=9ms, TR=50ms, Fig. 2).
Image processing was done using MIPAV (NIH, Bethesda, USA). Firstly, the background was masked out. For segmentation into grey and white matter (GM, WM), an automatic algorithm, Fantasm [8], was then used. This required some subsequent manual intervention. From the segmented images, the inner GM/WM cortical boundary and the outer GM/background boundary were determined (light blue lines in Fig. 1 and Fig. 2). Areas where the cortex should continue at the edges of the block were marked as so-called mirror points (Fig. 1, purple lines). The solution to the Laplace equation was calculated in three dimensions using home-built software [2].

Results:

It is obvious by inspection, that one can not choose an isocontour of the solution to the Laplace equation that does conform to the stria of Gennari in V1 (Fig. 2). Specifically, at the sulcal fundi the stria is closer to WM than the Laplace solution contours (red arrows in fig.2A), and at the gyral crowns the stria of Gennari is closer to the pial surface than the Laplace solution contours (red arrows fig.2B).
The Laplace solution also does not resemble the Bands of Baillarger, both of which are clearly visible in the image of M1/S1 (Fig.1).

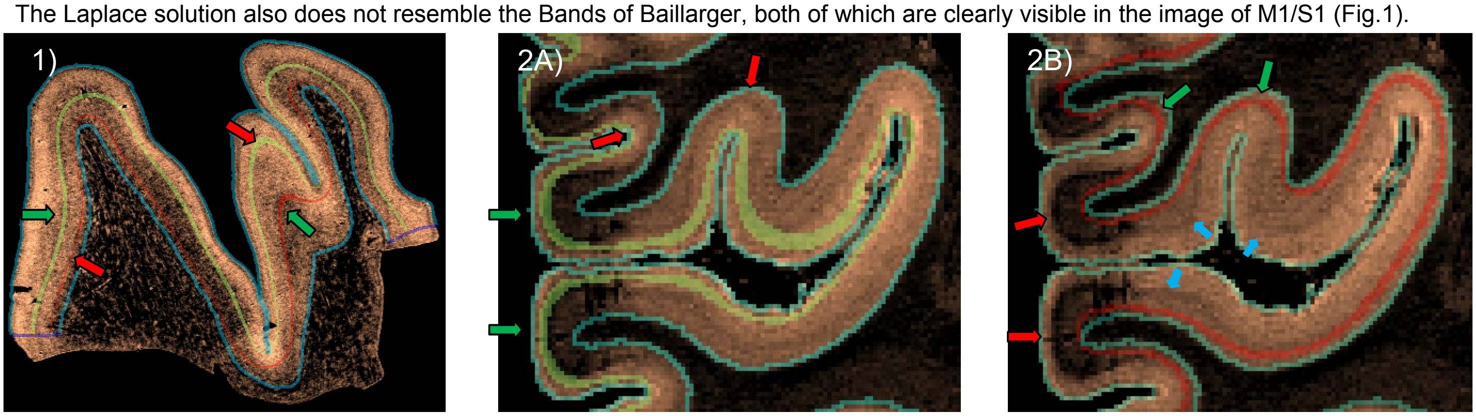

Fig. 1: pre- and postcentral gyrus (M1/S1), Fig. 2: occipital pole (V1). Stria of Gennari: blue arrows. Fig. 1 and Fig. 2: Isocontours (yellow and red lines) were chosen, so that they fit the bands as much as possible (green arrows). Obviously, they are not able to fit everywhere along the cortex (red arrows, fig. 1). A chosen isocontour does not fit at the fundus of sulci (red arrows, 2A) and at the crowns of the gyri simultaneously (red arrows, 2B).

Conclusion and discussion:

The Laplace equation was originally derived to describe electrostatics and steady-state heat flow. It is apparent that it does not correctly describe cortical layer structure. Is there a better way to model the structure of cortical layers? Hilgetag found, that the tension in corticocortical connections plays a major role in shaping the cortex [9]. Bok (1929) theorized (with experimental support) that sections within a given cortical layer preserve their volume, whether at a sulcal fundus, at a sulcal bank, or at a gyral crown [10]. Bok's volume preservation approach, which we are currently investigating, should better predict the actual conformation of cortical layers, and thus provide much more realistic profiles, since his description fits our observations very nicely.

References:

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