Cortical Mantle Volume Reconstruction from Cortical Surfaces

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Introduction

Software which is readily available to the neuroscience community can be used to reconstruct cortical surfaces from magnetic resonance imaging (MRI) data. Topologically correct cortical surfaces representing a white matter (WM) surface (which occurs at the white matter/gray matter interface) and a gray matter (GM) surface (which occurs at the gray matter/cerebrospinal fluid interface) can be created. Using these surfaces, we present an approach for producing a cortical mantle volume representing the gray matter. We then use this cortical mantle volume to restrict the analysis of functional MRI (fMRI) data to the gray matter. These results are then compared to a similar analysis using the entire masked volume.

Methods

In order to create a cortical mantle volume from MRI data, we require cortical surface representations of the white matter surface and gray matter surface. A cortical surface is represented by a triangulated mesh. FreeSurfer software [1] provides a pipeline for processing MRI data, including intensity correction, stripping and cortical surface reconstruction of the white matter. Topological defects in a surface (such as holes and handles) are corrected through an editing interface, resulting in a topologically correct "white" surface (referred to here as a WM surface). Subsequent processing with FreeSurfer uses this WM surface to produce a "pial" surface (referred to here as a GM surface). This GM surface has the same triangle mesh connectivity as the WM surface, only the embedding of the surface is different.

We processed 14 high resolution 1.5T T1-weighted anatomical MRI scans (0.86mm x 0.86mm x 1.00mm, Siemens Medical Systems) with FreeSurfer to produce topologically correct WM and GM surfaces. These scans were obtained as part of a static force BOLD fMRI experiment [2]. The WM and GM surfaces for each subject were then used to construct a cortical mantle volume representing the gray matter. By default, FreeSurfer translates a surface so the center of the MRI volume is located at the origin. We translated the surface back to "native" volume space so the surface coordinates are located within the original (i.e. native) MRI dimensions. The vertex locations of the triangles which compose the surface were then converted to voxel locations in a manner that ensures no voxel gaps, resulting in a voxel representation of the cortical surface. A region growing routine was used to identify all voxels enclosed within the WM surface voxel representation and also the GM surface voxel representation. Any voxels inside this enclosed WM voxel region were removed from the enclosed GM voxel region. The result is a voxel mask that represents voxels which belong to the GM surface, voxels which belong to the WM surface and voxels which belong in between the GM and WM surfaces. We call this voxel mask the cortical mantle volume mask.

The paradigm for BOLD fMRI data collection was a block design parametric static force protocol. Subjects were visually cued to alternate between resting quietly while passively viewing the visual feed-back screen (control state) and applying a randomly presented force level of 200g, 400g, 600g, 800g or 1000g with the right thumb and forefinger (force state). Beginning with a 45sec baseline period followed by a 4sec transition period, each force level stimulus was presented once for 45sec. This sequence was repeated for a total of 6 baseline periods, 5 transition periods and 5 force periods, giving a single subject run. Two runs were acquired for each subject. The fMRI runs were acquired using an EPI BOLD sequence (TR = 3986ms; TE = 60ms, 3.44mm x 3.44mm x 5.0mm voxel dimensions). Each fMRI volume was stripped of non-brain tissue and aligned to the first scan of each procedure using a 5-parameter alignment transformation. The result is a masked fMRI volume. Each masked volume was resampled into a Talairach reference space. Volumes were then smoothed by convolving each axial slice of each volume with a 2D Gaussian kernel, with a smoothing filter size of 2 voxels. See [2] for details. Each cortical mantle mask was also resampled into the same Talairach reference space.

FSL (version 3.2) / FEAT (version 5.4) [3] was used to perform a GLM analysis on each subject run. Due to the data preprocessing, most FSL processing options were not selected. For example, there was no slice timing correction performed, no motion correction, no spatial smoothing, no prewhitening, no intensity normalization and no registration. Temporal filtering and gamma convolution were selected.

Statistical parametric maps (SPMs) from the two single runs for each subject were first masked by the volume mask (i.e. both hemispheres). Correlation coefficients between the two SPMs generated for each single run were then computed. This procedure was repeated using the cortical mantle mask. Correlation analysis was performed using cortical mantle masks of the entire cortical mantle (i.e. both hemispheres). In addition, a correlation analysis between the two SPMs masked only by the left hemisphere cortical mantle of each subject were computed. Similarly, right hemisphere cortical mantle correlation coefficients were also computed.

Results

Figure 1 shows a cross-section of the resulting cortical mantle volume imposed on an MRI slice for the left hemisphere of a single subject. Figure 2 shows the correlation analysis using the volume mask and the cortical mantle mask. Table 1 presents the correlation coefficient results for all subjects.

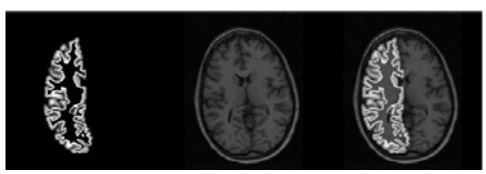

Figure 1: Cross-section of resulting cortical mantle volume (left) imposed on an MRI slice (right) for Subject 1.

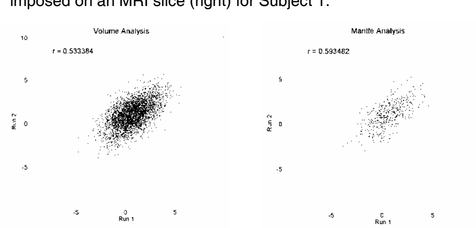

Figure 2: Correlation plots of Run 1 versus Run 2 for Subject 1. Results obtained by masking the SPMs with the volume mask are shown on the left and results obtained by masking the SPM with the cortical mantle mask are shown on the right.

A Wilcoxon signed-rank test indicates the correlation results in comparing the volume masked SPMs to the cortical mantle volume masked SPMs are significantly different ($p < 0.01$), and a paired t-test also indicates significant differences between the means ($p = 0.003$). A Wilcoxon signed-rank test comparing the left versus right mantle correlation results indicates the results are somewhat significant ($0.01 < p < 0.05$). A paired t-test on the means for left versus right cortical mantle results also supports this conclusion ($p = 0.032$).

Subject	Entire Volume (Left+Right)	Entire Mantle (Left+Right)	Left Mantle	Right Mantle
1	0.533	0.593	0.614	0.566
2	0.497	0.550	0.519	0.581
3	0.722	0.721	0.677	0.748
4	0.899	0.917	0.912	0.923
5	0.726	0.743	0.756	0.728
6	0.623	0.652	0.630	0.655
7	0.783	0.753	0.706	0.786
8	0.711	0.745	0.770	0.715
9	0.663	0.668	0.608	0.739
10	0.503	0.561	0.519	0.602
11	0.770	0.783	0.764	0.798
12	0.332	0.413	0.420	0.403
13	0.555	0.574	0.518	0.632
14	0.637	0.668	0.627	0.696
Mean	0.640	0.667	0.646	0.683
Variance	0.0213	0.0155	0.0169	0.0157

Table 1: Correlation coefficients of Run 1 versus Run 2 for each subject. SPMs were masked by a volume mask, a cortical mantle mask or a left or right hemisphere cortical mantle mask.

Discussion

We are using topologically correct cortical surfaces of the white matter and gray matter to construct a cortical mantle volume mask. Construction of a cortical mantle mask permits restricting analysis of fMRI data to the cortical mantle (or gray matter). This research represents an attempt at determining whether fMRI analysis that is restricted to the cortical mantle plays a significant role in the interpretation of fMRI results.

There have been a number of hypotheses regarding the possibility of improved functional localization results using cortical surfaces. However, one issue which has largely been ignored by the neuroscience community is how functional activation results should be projected onto a cortical surface. Some of the available software packages have built-in methods for doing this projection, but often documentation is sparse on the projection method chosen, or how the projection method affects the interpretation of results.

As a first step toward investigating this problem, we restricted the fMRI SPM analysis to the cortical mantle. These results indicate there is potentially a significant difference in the interpretation of fMRI results depending on whether the entire cortical volume is used or only the cortical mantle is used in the analysis. Further investigation which studies these effects in more detail is warranted.

References

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