Morphometric Analysis of Cortical Sulci Using Parametric Ribbons: A Study of the Central Sulcus

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Abstract: Interhemispheric and gender differences of the central sulcus were examined via a parametric ribbon approach. The central sulcus was found to be deeper and larger in the right nondominant hemisphere than in the left dominant hemisphere, both in males and in females. Based on its pattern, that asymmetry could be attributed to increased connectivity between motor and somatosensory cortex, facilitating fine movement, which could constrain the in-depth growth of the central sulcus. Position asymmetries were also found, which might be explained by a relative larger parietal association cortex in men but not in women. Index Terms: Central sulcus—Brain, cortex—Magnetic resonance imaging.

INTRODUCTION

The widespread use of modern tomographic imaging techniques, and particularly MRI, has allowed for the collection of large numbers of images of the human brain in vivo. Although many morphometric studies of the brain in normal and diseased states have been performed, most of them have relied on global or regional volumetric measurements. Recent developments in cortical reconstruction and mapping techniques (1–5) will allow a more extensive study and in-depth understanding of the cortical morphology.

The cerebral sulci have been of particular interest in morphometric studies during the last several years (6–12) for several reasons: First, the sulci are believed to form or be related to the boundaries of functional and cytoarchitectonic regions of the cortex (13,14), though it is questionable whether sulci can be reliably used to precisely define cytoarchitectonic and functional boundaries (15). However, it is likely that using the major sulci to obtain better spatial normalization methods for stereotaxic analysis will improve the overlap of corresponding cytoarchitectonic cortical regions across subjects and will therefore make statistical parametric analysis (16) of structure and function more sensitive in detecting focal atrophy or functional activity. Some evidence already exists that transformations that are more flexible than the piece-wise linear Talairach transformation (17) can improve overlap of microstructurally similar regions (18), even though the transformations used in that analysis were not flexible enough to precisely align cortical sulci to the degree that currently available methods do (7,8,14,19,20). Moreover, in the report of Rademacher (14), it was shown that there is a characteristic relationship between architectonic fields and sulci, gyri, and fissures.

Second, the shapes of the sulci are potentially related to the connectivity of the cortex. In particular, Van Essen (21) has proposed a theory of tension-based cortical folding, according to which the shapes of cortical sulci and gyri are determined in part by forces exerted by white matter fiber connections between various cortical regions. Figure 1 schematically demonstrates how the shape of a sulcus can be affected by the underlying white matter fibers. Following this hypothesis, studying the shapes of the cortical sulci is interesting from the perspective of understanding cortical morphogenesis but also from the perspective of understanding how disease or normal aging can affect cortical connectivity.

Third, the locations and shapes of cortical sulci can be altered by brain diseases, owing to an underlying, often selective atrophy of cortical regions that might cause the relative displacement and shape change of adjacent sulci. For example, Alzheimer patients displayed higher sulcal variability in temporoparietal projection areas as well as changes in the asymmetry of the Sylvian fissure (12).

Fourth, the sulci and gyri are natural routes to deep brain structures in certain neurosurgical procedures. In that respect, better understanding of the 3D structures of the sulci is important for image-assisted surgical plan-
ning and navigation. Some investigators have pursued nonparametric representation methods for this purpose (6,10).

In this article, we present a comprehensive study of the central sulcus, using MR images from 42 right-handed normal elderly subjects. We use a previously published methodology (9) for building parametric meshes of the central sulcus from cross-sectional images. A parametric mesh effectively places a coordinate frame on the sulcal surface, thereby allowing further shape analysis. We measured the area of the central sulcus, its depth profile, its position along the anterior/posterior direction, and its curvature profile. We present interhemispheric and gender differences in all of these measures.

MATERIALS AND METHODS

Subjects and Images

MR images from 42 healthy elderly individuals (22 men and 20 women) were acquired on a GE Signa 1.5 T scanner. All subjects were participants in the Baltimore Longitudinal Study of Aging (22,23). The subjects were selected from a very narrow age range to minimize age effects on our analysis; the average age was 65.6 ± 2.8 years for the men and 66.6 ± 3.1 years for the women. All subjects were right-handed, as determined by the 10 item Edinburgh Inventory (24). The MR images were acquired using a 3D spoiled GRASS (SPGR) acquisition in the axial plane. Imaging parameters were as follows: TR = 35 ms, TE = 5 ms, flip angle = 45°, matrix = 256 × 256, field of view = 24 cm, 1 excitation. The resulting voxel size was 0.94 × 0.94 × 1.5 mm. After acquisition, the images were reoriented to be parallel to the anterior/posterior commissure line and were transferred to a Silicon Graphics Indigo2 Unix workstation for image processing.

Definition of Sulci

The central sulcus of all subjects was extracted manually for both hemispheres, by tracing the medial surface in between two juxtaposed banks of the sulcus (9). Figure 2 shows a typical cross-section of a tracing of a sulcus overlaid on the corresponding MR image; tracing was performed so that the resulting surface was symmetrically positioned with respect to the opposite banks of the sulcus. With use of the method described (9), parametric representations of the sulci were then constructed. In particular, a canonical grid was placed on each sulcus, as demonstrated in Fig. 3. The parametric lines of this grid were stretched via an iterative algorithm (25) so that they were evenly spaced along the horizontal and the vertical lines. All horizontal parametric curves were joined in two endpoints of the parametric grid, as shown in Fig. 3. These two endpoints lie along the outer edge of the sulcus, that is, along the exposed part of the central sulcus. One of the endpoints of the sulcus was close to the interhemispheric fissure, and the other was close to the Sylvian fissure. Since the MR images, and therefore the tracings of the sulci, were not acquired isotropically, the traced sulci were rescaled according to the voxel dimensions reported above, so that all subsequent measurements were in millimeters.

Area and Depth Measurements

Area measurements were obtained via integration along the parametric grid. More specifically, the parametric grid lines were traversed and the area of each quadrilateral patch was cumulatively added to produce a figure for the total area. Normalized differences in area were also computed as (left − right)/0.5(left + right).

To measure the depth of the sulcus, we developed a dynamic programming algorithm, which was already presented in detail (9) and summarized next; we will refer to this algorithm as the depth estimation algorithm (DEA). Since the depth of the sulcus varies throughout its extent, DEA considers each point along the outer edge of the sulcal surface in between two juxtaposed banks of the sulcus (9). Figure 2 shows a typical cross-section of a tracing of a sulcus overlaid on the corresponding MR image; tracing was performed so that the resulting surface was symmetrically positioned with respect to the opposite banks of the sulcus. With use of the method described (9), parametric representations of the sulci were then constructed. In particular, a canonical grid was placed on each sulcus, as demonstrated in Fig. 3. The parametric lines of this grid were stretched via an iterative algorithm (25) so that they were evenly spaced along the horizontal and the vertical lines. All horizontal parametric curves were joined in two endpoints of the parametric grid, as shown in Fig. 3. These two endpoints lie along the outer edge of the sulcus, that is, along the exposed part of the central sulcus. One of the endpoints of the sulcus was close to the interhemispheric fissure, and the other was close to the Sylvian fissure. Since the MR images, and therefore the tracings of the sulci, were not acquired isotropically, the traced sulci were rescaled according to the voxel dimensions reported above, so that all subsequent measurements were in millimeters.

FIG. 1. A schematic diagram showing the potential effects on the shape of a sulcus of increased cortical connectivity.

FIG. 2. A typical example of a cross-section of the traced central sulcus.
(exposed) edge of the central sulcus sequentially, and it obtains an estimate of the depth of the sulcus for that point. Effectively, DEA places a flexible probe on each point along the outer edge of the sulcus. The probe adapts to the curvature of the sulcus from the outer edge to the root. Therefore, the depth estimate obtained by DEA for a particular point along the outer edge of the sulcus is equal to the length of a trajectory joining that point with some point along the root of the sulcus. This latter point on the root of the sulcus is determined automatically via a dynamic programming algorithm. The cost function minimized in this dynamic programming algorithm includes two terms: The first term favors trajectories of minimal length, while the second term favors trajectories that lie on a plane that is perpendicular to the sulcus and pass through the point on which the depth is being estimated. Combined, these two terms favor paths that are orthogonal to the long axis of the sulcus, so that they resemble depth probes, and that take short paths terminating on the root of the sulcus. An example of a number of depth probes estimated this way is shown in Fig. 4A. A plot of the corresponding depth estimates is shown in Fig. 4B.

We compared the depths of the left and the right central sulci in the female and the male groups with and without normalization for average depth of the sulcus. This allowed us to look at relative differences in depth estimates along the central sulcus. Statistical comparisons of depth measurements were performed via point-wise \( t \) tests on each point along the outer edge of the central sulcus, where depth measurements were obtained.

**Positional Asymmetry**

We measured the position of the central sulcus along the anterior/posterior direction to determine potential left/right asymmetries. Since such asymmetries might be present in certain areas along the sulcus but not in others, we obtained an asymmetry measure for each point of the parametric grid. In particular, we measured the left/right difference in the anterior/posterior direction, normalized by the total distance between the anterior-most and posterior-most points of the brain. We then calculated point-wise \( t \) tests on the points of the parametric grid to display, in a uniform way, regions that displayed significant differences; we selected a single central sulcus on which we displayed such regions color-coded. This sulcus was the average central sulcus (right hemisphere), that is, the central sulcus resulting by averaging the position of each point on the parametric grid across subjects. We colored this average sulcus by the \( p \) value of these \( t \) tests to display the regional patterns of variation. We note that the color-coded renderings of the average central sulcus...
are simply for visualization purposes, to allow the reader to better understand approximately where along the central sulcus significant effects were found. The sulci in these displays are oriented as in Fig. 3.

Curvature Measurements

To quantify the degree of folding of the central sulcus, we measured the two principal curvatures on each grid point along the sulcus. We refer to these curvatures as \( k_1 \) and \( k_2 \). Because of the way that the ribbons were parameterized, the surface normal pointed in the general posterior/anterior direction. Therefore, for folds oriented roughly from anteriorly to posteriorly, such as the pre-central knob (26), the first principal curvature, \( k_1 \), is the one displaying high and positive values and it is the one reflecting the degree of folding of the sulcus. Conversely, folds with the opposite orientation display very low and negative value of \( k_2 \), and the absolute value of \( k_2 \) reflects the degree of folding of the sulcus, around those folds. Therefore, for either type of fold, the absolute value of \( k_1 \) and \( k_2 \) reflects the degree of folding in the respective direction.

To obtain a robust curvature measurement, we used an adaptive least squares estimation procedure in which we fit a quadratic patch around each point of the central sulcus (9,19). The size of the patch was estimated adaptively. In particular, we used the maximum possible patch for which the error of fit of the least squares estimation procedure did not exceed a prespecified value of 1 mm. This means that the maximum, for a given approximation error, noise removal smoothing was applied, while not washing out the details of the shape of the sulcus.

RESULTS

Area Measurements

The average area of the central sulcus for men was 1,567.45 ± 128.6 mm\(^2\) (left hemisphere) and 1,602.92 ± 149.6 mm\(^2\) (right hemisphere). There was no significant difference in absolute area measurements between left and right hemispheres as measured by a \( t \) test. The average normalized difference \([\text{right} - \text{left}] / 0.5(\text{right} + \text{left})\) was 0.0074. The difference in the normalized area measurements between the two hemispheres barely reached significance (\( p = 0.05 \)), with the right central sulcus having relatively larger normalized area than the left. The trend was similar for women. Specifically, the average area of the central sulcus was 1,499.5 ± 144 mm\(^2\) (left hemisphere) and 1,539.75 ± 120 mm\(^2\) (right hemisphere). A \( t \) test for the left/right difference in the absolute values of the area approached significance (\( p = 0.056 \), right > left). A \( t \) test for the normalized area differences gave highly significant difference between right and left (\( p = 0.0006 \), right > left).

Depth Measurements

The depth profile along each sulcus was recorded in millimeters. An index running from 0 to 120 was assigned to each position along the central sulcus, with 0 corresponding to the endpoint close to the Sylvian fissure and 120 to the endpoint close to the interhemispheric fissure. The average depth for each hemisphere was calculated for men and women and is plotted in Fig. 5A for the men and Fig. 5B for the women. To further examine the apparent difference in the depth profiles, we performed point-wise \( t \) tests along each point of the outer edge of the central sulcus. In Fig. 6, we plot the resulting
(two-sided) p value for men (Fig. 6A shows regions where right > left and Fig. 6B shows regions where left > right) and women (Fig. 6C and D, respectively).

For the normalized depth measurements, that is, of the measurements (right or left depth)/(average of left and right), results are shown in Fig. 7, in a arrangement analogous to the one of Fig. 6. The observed trends are the same. However, the significance level is slightly higher for the normalized depth values, as expected, since interindividual variability in overall size was eliminated.

We finally measured the average depth along the central sulcus (average of the depth curves in Fig. 5). The average depths for the men were 21.07 mm (right hemisphere) and 20.6 mm (left hemisphere). The corresponding measurements for women were 20.94 mm (right hemisphere) and 20.04 mm (left hemisphere).

**Position Asymmetries**

The results for the position along the anterior/posterior direction were different for men and women. Specifically, Fig. 8 shows the average right central sulcus, which, as explained in Materials and Methods, we simply use as a reference for displaying the results of the statistical analysis, color-coded by the p value of the left/right asymmetry. Red are the regions of significant interhemispheric asymmetry. These statistical maps indicate that in men, the central sulcus is located more anteriorly in the left hemisphere. This was the case for the part of the sulcus that is close to the Sylvian fissure and for the area around the knob. In women, however, the result was the opposite. In particular, the central sulcus was located more posteriorly in the left hemisphere compared with the right hemisphere. The same analysis indicated no regions of significance with either a more posterior male left central sulcus or a more anterior female left central sulcus. It is important to note that the areas that appear to be red (highest significance) in Fig. 8A are blue in Fig. 8B. Keeping in mind that Fig. 8A and B pertain to the converse hypothesis (right posterior to left in Fig. 8A versus right anterior to left in Fig. 8B), this reveals a common trend between men and women, namely, that the area very close to the Sylvian fissure and...
the one around the precentral knob tended to be more anteriorly located in the left hemisphere relative to the other regions of the sulcus. However, women also displayed an across-the-board trend for more anteriorly located right central sulcus. Hence, only the relative position with respect to other sulcal regions displayed a similar pattern between men and women.

The left/right position asymmetries are visually demonstrated in Fig. 9, which displays a surface rendering of the average brain shape of each group overlaid on the average left and central sulci for males and females. The brain is viewed from inferiorly in Fig. 9. Figure 10 shows cross-sections of the average central sulci, after affine transformation to Talairach space, overlaid on the Talairach plates at three representative levels. The horizontal lines in the first two rows were placed in the positions that demonstrated significant interhemispheric differences in men; the arrows indicate the knob. Figure 10 might be a useful guide in interpreting functional imaging experiments since it provides an indication of the expected location of the primary motor and somatosensory cortices in Talairach space.

**Curvature Measurements**

The right central sulcus displayed, in general, higher curvature than the left central sulcus. This was the case for both the anteriorly and the posteriorly oriented folds of the sulcus and was particularly pronounced around the region of the precentral knob, the area in which the hand is believed to be represented. The pattern was very similar for men and women. Figure 11 shows the color-coded p value, overlaid on the same average sulcus, for men and women. Figure 11 (top) corresponds to the principal curvature that reflects folding in the anterior/posterior direction and Fig. 11 (bottom) the converse. There were no regions of significantly higher curvature of the left central sulcus for either men or women.
DISCUSSION

Area and Depth Measurements

The area and depth measurements are quite interesting. There was a general trend for the right central sulcus to be deeper and larger than the left central sulcus in both males and females. One might expect the opposite since the left hemisphere was dominant in these subjects. However, how deep a sulcus grows might depend largely on constraints from the underlying white matter fibers. A theory that supports this hypothesis has been suggested (21), where it was argued that axonal tension forces and the need of the brain to minimize length of connections largely shape the cortical convolutions. Under that hypothesis, an increased connectivity between juxtaposed sides of the central sulcus would tend to constrain the inward growth of the cortex and hence to reduce the depth of the central sulcus (see Fig. 1). Our results support this hypothesis. In particular, for fine movements of the fingers (object manipulation) and lips (speech), one would expect a relatively higher degree of connectivity between the motor and sensory cortices, which presumably is manifested by the relatively lower depth of the central sulcus in the corresponding regions along the somatotopic representation. For example, Fig. 5 shows a sharp decrease in depth somewhere around the middle of the sulcus (around index 60, in the plots of Figs. 5–7), which is where the knob is located and where the fingers are represented (27). This decrease in depth was characteristic in all the subjects we studied, and it is hence reflected by the average depth curves of Fig. 5. This is an area where we expect to have the highest connectivity between the motor and sensory cortices, which would facilitate fine object manipulation. The area right below that is where the face is represented, a large part of which is devoted to the lips, also an area where we would expect a high degree of connectivity between the motor and sensory cortices, facilitating speech.

We should stress that our hypothesis cannot be fully supported by our current data, owing to the limited information about fiber connections that is provided by standard structural imaging protocols. However, developments in diffusion tensor imaging for white matter fiber tracking (28,29) should make it possible to further...
investigate the relationship between increased white matter connectivity and morphologic characteristics of the central and other sulci.

**Position Asymmetries**

There were evident position asymmetries in the central sulcus, and these asymmetries were gender dependent, as shown by Fig. 8. We note, however, that the positional asymmetries were far less pronounced than the depth asymmetries. For the males, the right knob was more posteriorly located than the left. No significant difference was measured in the same area for females. Coupled with the fact that the curvature of the right knob was higher than the left and with the 3D displays of Fig. 9, this implies that the fold of the area in which the hand is represented is slightly more pronounced in the right hemisphere relative to the left. One possible explanation is that a relatively larger volume of the speech parietal association (Wernicke) areas of the left hemisphere restricts the growth, or at least the folding, of the knob. Previous studies have demonstrated a larger inferior parietal lobule volume (30), which could explain this asymmetry. Figure 9 demonstrates some of the position asymmetries very vividly.

The comparison of the patterns of positional asymmetries between males and females is interesting. The male trend of relatively more anterior left central sulcus, which is in agreement with the expected increased speech parietal association areas, was not present in women. One explanation is that if the hypothesis of a relatively more bilateral processing of language and spa-
tial functions in females were true, then a higher symmetry in the corresponding cortical regions would be expected, which would eliminate the asymmetry found in males. This is supported by measurements of interhemi-
spheric connectivity via shape analysis of the corpus cal-
losum (31).

Our results are in contrast with those presented by
Amunts et al. (32), where the left central sulcus was
found to be deeper in right-handed males. This discrep-
ancy might be due to methodological differences in mea-
suring the depth of the central sulcus or to differences in
the ages of the subjects in the two studies. In particular,
the methodology adopted in that work (32) measured
depth from axial cross-sections oriented parallel to the
anterior/posterior commissure plane. However, axial sec-
tions are not oriented along the depth of the central sul-
cus, particularly superiorly in the brain, which is the area
where significant depth differences were found (32). In
contrast, our analysis used a 3D parametric representa-
tion of the central sulcus in conjunction with a dynamic
programming algorithm, which allowed us to measure
the true depth of the sulcus (see Fig. 4A), independently
of the orientation of the volumetric images. Moreover, in
that work (32), the images were transformed via a piece-
wise linear transformation to the Talairach space prior to
obtaining the depth measurements. This standardization
procedure can potentially differentially change the size
of the central sulcus. For example, if the position of the
central sulcus relative to the anterior commissure and
posterior commissure landmarks is different, which is the
case according to our anterior/posterior position mea-
surements, then the left and right central sulci might be
subjected to different scaling, which would differentially
change their size. In contrast, our depth measurements
were performed directly on the original data and normal-
ized afterward, according to global size. Finally, in con-
trast to the work of Amunts et al. (32), aging might
differentially affect the shape of the central sulcus in men
and women or in the left and right hemispheres, which
would explain differences in the findings of the two
studies.

One limitation of our study is the lack of left-handed
subjects. Analysis of left-handed subjects in future stud-
ies will be particularly helpful in strengthening our hy-
pothesis on the relationship between the local depth de-
crease in the knob, which is often manifested as a sulcal
interruption, and increased connectivity between adja-
cent cortical regions. Moreover, we plan to use probabi-
listic maps of white matter connectivity (28), with dif-
fusion tensor imaging (29), to better investigate the re-
lationship between sulcal morphology and underlying
white matter fiber pathways.

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