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1703 Location of the Central Sulcus via Cortical Thickness of the Precentral and Postcentral Gyri on MR

Joel R. Meyer, Sudipta Roychowdhury, Eric J. Russell, Cathy Callahan, Darren Gitelman, and M. Marsel Mesulam

PURPOSE: To determine whether relative cortical thickness measurements of the precentral and postcentral gyri can be used to differentiate the central sulcus from adjacent cortical sulci. **METHODS:** Turbo inversion-recovery MR imaging of the entire brain was done with scans parallel to the anterior commissure–posterior commissure line. Cortical thickness was measured in each hemisphere with a jeweler's eyepiece with 0.1-mm gradations. Three measurements were obtained perpendicular to the central, precentral, and superior frontal sulci, as determined by means of established anatomic methods. The ratios of cortical thickness on both sides of the central, precentral, and superior frontal sulci were calculated and compared. **RESULTS:** The mean ratio of precentral/postcentral gyri was 1.64 for the right hemisphere and 1.53 for the left hemisphere. The mean cortical thickness ratios were as follows: 1.01 for the right hemisphere and 1.01 for the left hemisphere across the precentral sulcus, and 1.03 for the right hemisphere and 0.99 for the left hemisphere across the superior frontal sulcus. **CONCLUSION:** Cortical thickness measurements across the central sulcus provide a method for locating the primary motor (precentral gyri) and primary somatosensory (postcentral gyri) cortices. The higher mean cortical thickness ratio across the central sulcus corresponds with known cytoarchitectonic relationships.

Index terms: Brain, anatomy; Brain, gyri; Brain, magnetic resonance

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Identification of the precentral and postcentral gyri on magnetic resonance (MR) images is important for precise anatomic location of the motor cortex, especially when surgical intervention is being planned. This is typically accomplished by identifying the central sulcus by its surface landmarks. The precentral gyrus forms the anterior bank of the central sulcus and corresponds to the primary motor cortex (Brodmann area 4) (1, 2); the postcentral gyrus forms the posterior bank and corresponds to the somatosensory area (Brodmann areas 3, 1 and 2) (1, 2).

Some authors have identified the precentral and postcentral gyri on the basis of the topography of adjacent sulci (3, 4); others have identified

a characteristic branching pattern of the cerebral white matter on cross-sectional computed tomographic (CT) scans and MR images (5). The purpose of this study was to determine whether relative cortical thickness measurements across the banks of the central sulcus, assessed on high-resolution turbo inversion-recovery (IR) MR images of the brain, could provide an alternative and more direct anatomic method for locating the central sulcus and, therefore, the precentral and postcentral gyri.

Materials and Methods

Informed consent was obtained from 10 healthy volunteers. MR imaging of the entire brain was done on a 1.5-T system using the following turbo-IR protocol: 2010/18/2 (repetition time/echo time/excitations), inversion time of 300, turbo factor of 3, matrix of 512, field of view of 280, and section thickness of 5 mm. Images were obtained in the transverse axial plane parallel to the anterior commissure–posterior commissure (AC-PC) line (Fig 1). The real image data were used for reconstructing the MR images.

Identification of the central, precentral, and superior frontal sulci was established by consensus between two observers and was based on previously established ana-

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From the Departments of Radiology (J.R.M., S.R., E.J.R., C.C., D.G.) and Neurology (J.R.M., D.G., M.M.M.), Northwestern University Medical School, Chicago, Ill.

Address reprint requests to Joel R. Meyer, MD, Department of Radiology, Evanston Hospital, 2650 Ridge Ave, Evanston, IL 60201.

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tomic methods (3–6). Serial measurements of the thickness of the gray matter were obtained across these three sulci in both hemispheres on four contiguous axial images of the brain (Fig 2). Three sets of measurements of the gray matter thickness were obtained for each subject across all sulci in each of the four sections of both hemispheres. Medial, middle, and lateral measurements were obtained for the precentral and central sulci, which are perpendicular to the long axis of the brain. For the superior frontal sulcus, which is parallel to the long axis of the brain, anterior, middle, and posterior measurements were obtained. Each measurement was acquired perpendicular to the sulcus in order to minimize partial volume artifacts. The measurements were obtained on film by using a jew-

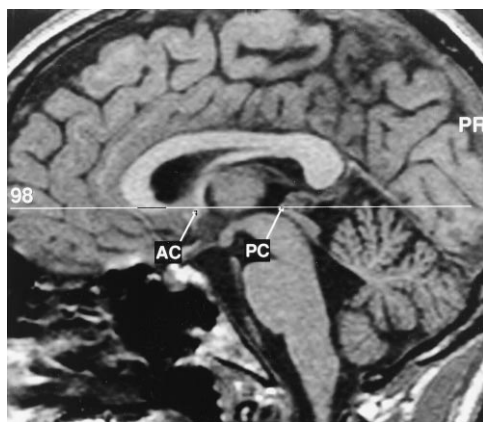


Fig 1. Midline sagittal fast field-echo MR image shows the orientation of the anterior commissure–posterior commissure (AC-PC) line. All axial images were obtained parallel to this line.

eler's eyepiece with 0.1-mm gradations and then converted into true anatomic dimensions by using the magnification factor for each case. When a sulcus was not seen on one of the four scans in an individual subject, measurements were not obtained.

Relative cortical thickness ratios were calculated by dividing the cortical thickness along the anterior bank of the sulcus by the cortical thickness along the posterior bank of the sulcus for the central and precentral sulci. For the superior frontal sulcus, the relative cortical thickness ratio was calculated by dividing the cortical thickness along the medial aspect of the superior frontal sulcus by the cortical thickness along the lateral aspect of the sulcus. Mean cortical thickness ratios were calculated for the nine sulcal locations in each cerebral hemisphere. Statistical analysis of the data was performed using an unpaired Student's *t* test.

Results

Six men and four women with a mean age of 31 years participated in the study. All the subjects were right-handed, as established on the basis of the Edinburgh questionnaire. Excellent-quality T1-weighted turbo-IR MR images of the brain were obtained in all subjects (Figs 3 and 4). A total of 216 measurements of gray matter thickness were made across the central sulcus, 111 in the right hemisphere and 105 in the left hemisphere. One hundred eighty-five cortical thickness measurements were obtained across

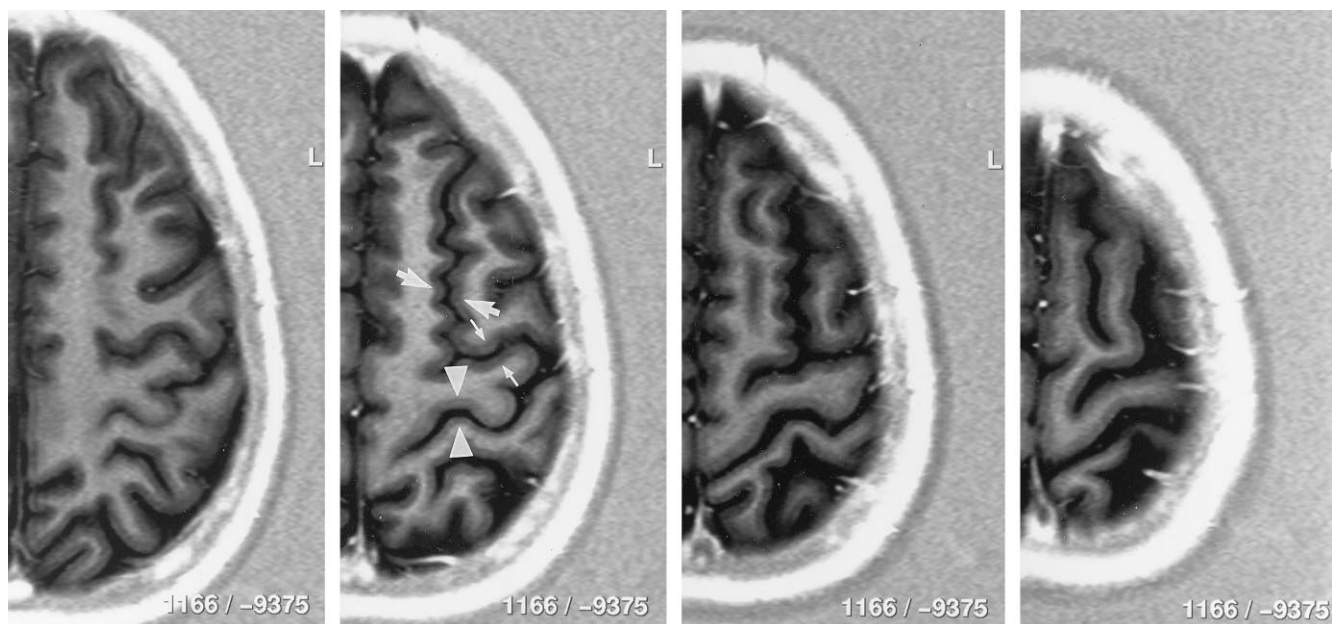


Fig 2. Four contiguous axial turbo-IR MR images of the brain (2010/18/2, inversion time of 300) show the levels at which cortical thickness was evaluated. Note the excellent gray–white matter differentiation with the turbo-IR technique, which facilitates measurement of gray matter thickness. Arrowheads indicate central sulcus; small arrows, precentral sulcus; and larger arrows, superior frontal sulcus.

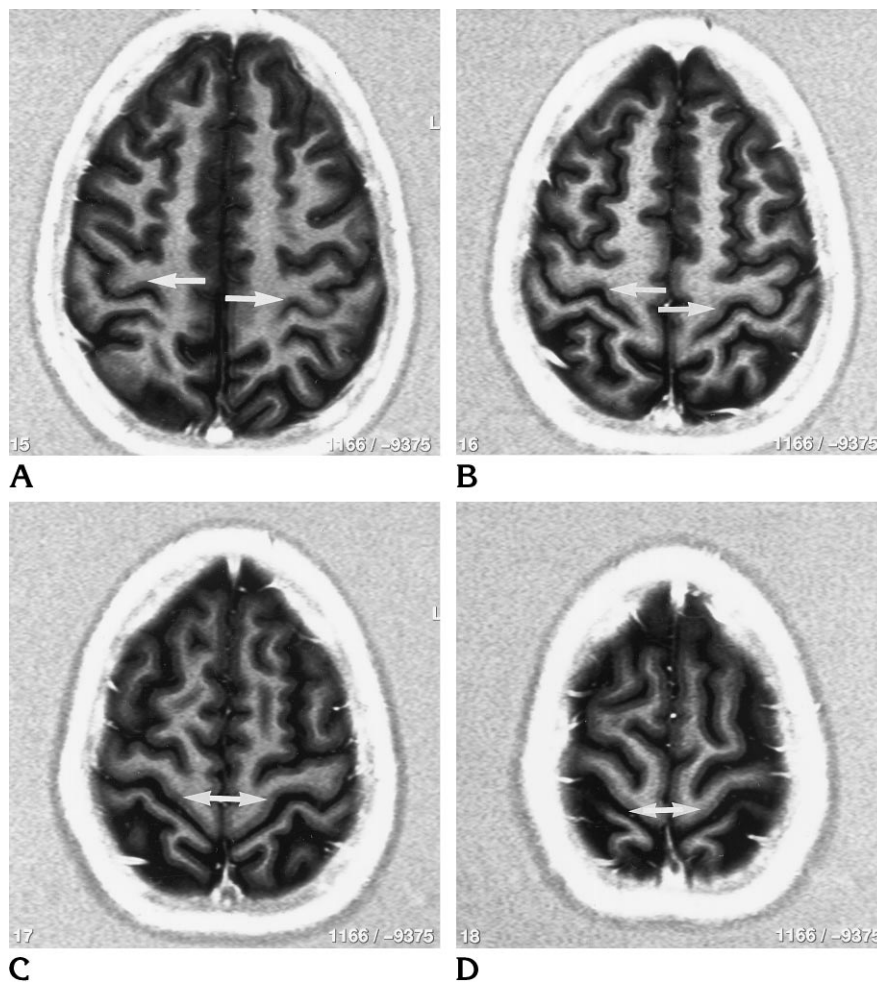


Fig 3. MR images of one of the subjects included in this study. Identification of the central sulcus (arrows) is facilitated by evaluating differences in cortical thickness. The anterior bank motor cortex is much thicker than the posterior bank sensory cortex.

the precentral sulcus, 99 in the right hemisphere and 86 in the left hemisphere. One hundred sixty-eight measurements were obtained across the superior frontal sulcus, 87 in the right hemisphere and 81 in the left hemisphere. For each subject, the mean cortical thickness measurements and the mean cortical thickness ratios with regard to the particular sulcus and hemisphere are presented in the Table.

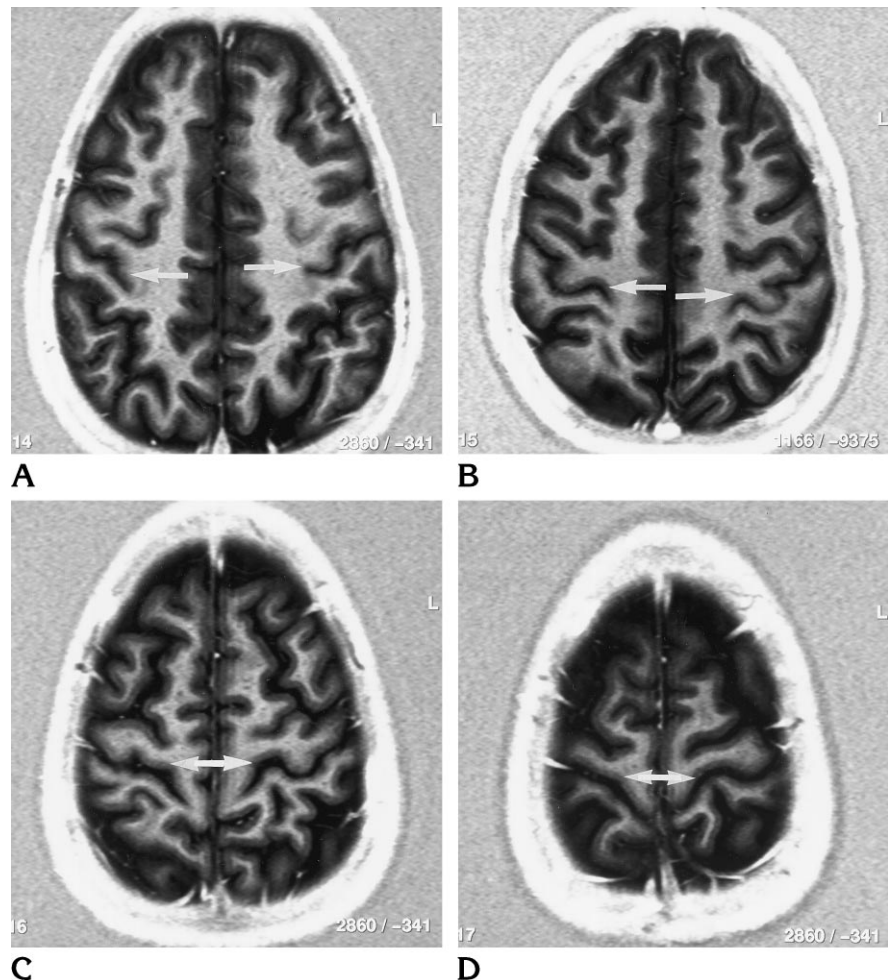
The mean cortical thickness measurements (Table) for the anterior and posterior banks of the central sulcus were 2.70 and 1.76 mm (both hemispheres), 2.72 and 1.70 mm (right hemisphere), and 2.69 and 1.81 mm (left hemisphere), respectively. For the precentral sulcus, thickness measurements for the gray matter in the anterior and posterior cortices were 2.48 and 2.46 mm (both hemispheres), 2.51 and 2.50 mm (right hemisphere), and 2.44 and 2.43 mm (left hemisphere), respectively. Cortical thicknesses across the superior frontal sulcus were 2.50 and 2.48 mm (both hemispheres),

2.55 and 2.46 mm (right hemisphere), and 2.46 and 2.49 mm (left hemisphere) for the medial and lateral banks, respectively.

Statistical analysis with an unpaired Student's *t* test yielded significant differences ($P < .0001$) for the thickness measurements in the anterior and posterior cortices of the central sulcus. There were no significant differences between the gray matter thickness measurements between the anterior and posterior banks of the precentral sulcus or the medial and lateral banks of the superior frontal sulcus. There were significant differences ($P < .0001$) when comparing either the anterior or posterior banks of the central sulcus with the anterior and posterior banks of the precentral sulcus as well as the medial and lateral banks of the superior frontal sulcus. There were no significant differences between the hemispheres in any of the measurements.

The mean cortical thickness ratios (Table and Fig 5) across the central sulcus (precentral

Fig 4. MR images of another of the subjects included in this study. Identification of the central sulcus (arrows) is facilitated by evaluating differences in cortical thickness. The anterior bank motor cortex is much thicker than the posterior bank sensory cortex.



gyrus/postcentral gyrus) were 1.54 (both hemispheres), 1.64 (right hemisphere), and 1.53 (left hemisphere). For the precentral sulcus (anterior/posterior gyri), the ratios were 1.00 (both hemispheres), 1.00 (right hemisphere), and 1.01 (left hemisphere). The mean cortical thickness ratios across the superior frontal sulcus (medial/lateral gyri) were 1.01 (both hemispheres), 1.03 (right hemisphere), and 0.99 (left hemisphere).

Discussion

Identification of the central sulcus indicates the location of the precentral and postcentral gyri. There is considerable interest in this region because the primary motor area (Brodmann area 4) typically occupies the precentral gyrus, while the primary somatosensory areas (Brodmann areas 3, 1 and 2) are located within the postcentral gyrus (1, 2). The central sulcus also

separates the frontal and parietal lobes of the cerebral hemisphere.

Previous investigators have described a variety of topographic criteria for the identification of the central sulcus with the use of plain radiography, pneumoencephalography, angiography, CT, and MR imaging. Kido et al (3) discovered a method for locating the central sulcus on axial CT scans that involves identification of the superior frontal sulcus, which separates the superior and middle frontal gyri. The posterior end of the superior frontal sulcus intersects and forms a right angle with the precentral sulcus. The sulcus immediately posterior to the precentral sulcus is then identified as the central sulcus. Iwasaki et al (5) described a method to identify the precentral and postcentral gyri on CT scans and MR images based on the branching pattern of the medullary white matter. These authors identified six branches of the medullary white matter at the level of the centrum semi-

Absolute cortical thickness measurements and relative cortical thickness ratios

Subject	Age, y	Handedness Hemisphere*	Central Sulcus			Precentral Sulcus			Superior Frontal Sulcus		
			Anterior, mm	Posterior, mm	Ratio	Anterior, mm	Posterior, mm	Ratio	Medial, mm	Lateral, mm	Ratio
1	29	Both	3.23	2.19	1.48	2.75	2.68	1.03	2.88	2.84	1.01
		R	3.10	1.99	1.56	2.80	2.78	1.01	2.64	2.62	1.01
		L	3.46	2.39	1.45	2.70	2.57	1.05	3.12	3.06	1.02
2	25	Both	2.73	1.78	1.54	2.43	2.33	1.05	2.64	2.49	1.06
		R	2.95	1.81	1.63	2.34	2.29	1.02	2.61	2.43	1.08
		L	2.51	1.74	1.45	2.52	2.37	1.07	2.67	2.55	1.05
3	36	Both	2.50	1.56	1.60	2.38	2.37	1.01	2.19	2.20	1.00
		R	2.59	1.51	1.71	2.62	2.49	1.05	2.45	2.38	1.03
		L	2.40	1.61	1.49	2.15	2.24	0.96	1.93	2.01	0.96
4	34	Both	2.62	1.62	1.61	2.47	2.44	1.01	2.43	2.45	0.99
		R	2.57	1.56	1.64	2.68	2.64	1.02	2.83	2.66	1.06
		L	2.66	1.68	1.58	2.26	2.24	1.01	2.03	2.24	0.91
5	28	Both	2.50	1.53	1.63	2.55	2.49	1.02	2.51	2.53	0.99
		R	2.67	1.50	1.77	2.52	2.52	1.00	2.63	2.55	1.03
		L	2.33	1.55	1.50	2.59	2.47	1.05	2.40	2.52	0.95
6	38	Both	2.73	1.79	1.53	2.42	2.46	0.99	2.33	2.33	1.00
		R	2.68	1.69	1.59	2.54	2.66	0.95	2.39	2.42	0.99
		L	2.77	1.88	1.47	2.31	2.25	1.03	2.28	2.25	1.01
7	28	Both	2.44	1.52	1.61	2.44	2.49	0.98	2.65	2.59	1.02
		R	2.51	1.64	1.53	2.44	2.47	0.99	2.72	2.64	1.03
		L	2.37	1.40	1.70	2.44	2.52	0.97	2.57	2.55	1.01
8	26	Both	2.78	1.79	1.56	2.62	2.62	1.00	2.31	2.32	0.99
		R	2.71	1.75	1.55	2.66	2.50	1.07	2.28	2.18	1.04
		L	2.86	1.84	1.56	2.57	2.73	0.94	2.33	2.46	0.95
9	25	Both	2.62	1.84	1.42	2.47	2.55	0.97	2.70	2.74	0.99
		R	2.70	1.79	1.51	2.47	2.45	1.01	2.64	2.59	1.02
		L	2.55	1.90	1.34	2.48	2.64	0.94	2.76	2.90	0.95
10	36	Both	2.76	1.89	1.46	2.26	2.38	0.95	2.31	2.24	1.03
		R	2.72	1.89	1.44	2.04	2.16	0.94	2.30	2.15	1.07
		L	2.82	1.88	1.50	2.48	2.60	0.96	2.32	2.32	1.00

* All subjects were right-handed.

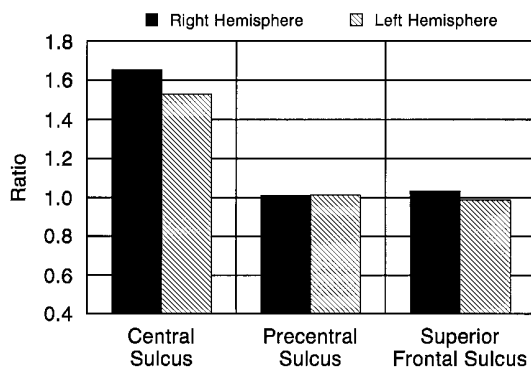


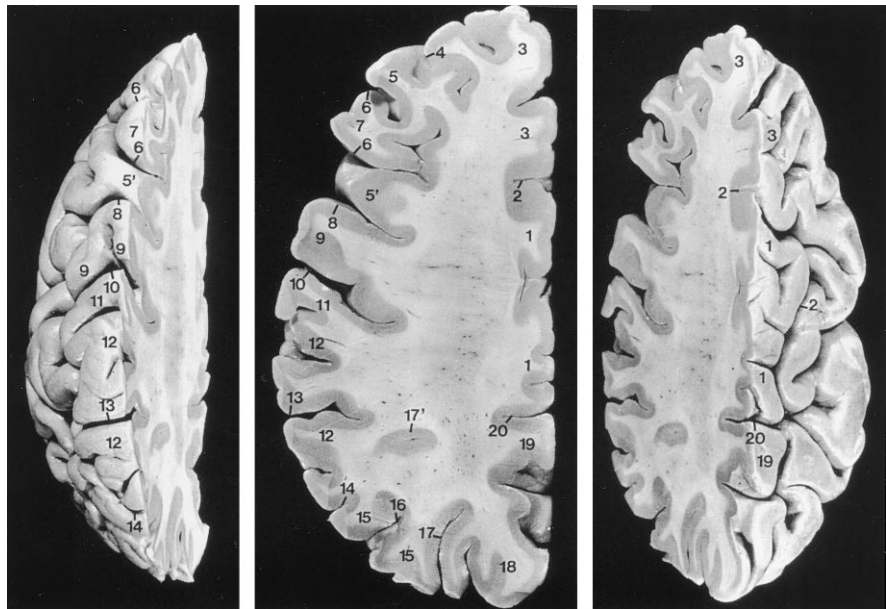
Fig 5. Mean cortical thickness ratios.

ovale that allowed identification of the superior and middle frontal gyri, the precentral and postcentral gyri, and the inferior parietal lobule and precuneus. This branching pattern changes as one moves toward the convexity, where only four medullary white matter branches are identified corresponding to the superior frontal gyrus, precentral gyrus, postcentral gyrus, and

precuneus. Recently, Naidich et al (6) described the pars bracket on the basis of identifying the pars marginalis of the cingulate sulcus on axial images. The central sulcus projects medially and anteriorly to the pars marginalis and falls within the pars bracket.

Our method of locating the central sulcus and the precentral and postcentral gyri differs from the above methods in that it involves the direct evaluation of gray matter thickness across the banks of the central sulcus and is therefore directly related to the cytoarchitectonic features of the relevant cortical area. It has been known for some time that the cerebral cortex is not uniform throughout the brain: it consists of a number of areas that differ in cytoarchitecture, function, and cortical thickness (1, 2). The most widely used cytoarchitectonic map was developed by Brodmann (7), who divided the cerebral cortex into 47 areas on the basis of variations of neuronal architecture. Later, von

Fig 6. Axial anatomic section shows the marked difference in cortical thickness across the banks of the central sulcus (9) (from Duvernoy [15]).



Economo (1, 2, 8) established that all cortical areas can be divided into five fundamental patterns that depend on the relative distribution of granule and pyramidal cells. Agranular cortex (von Economo type 1), which is predominant in the primary motor cortex (Brodmann area 4), is characterized by the giant pyramidal cells of Betz in cortical layer V and by the relative absence of granule cells (1, 2, 8). This area is typically the thickest portion of the cerebral cortex (1, 2, 7, 8) (Fig 6). In contrast, granular cortex (von Economo type 5), found in primary sensory areas, such as Brodmann areas 3, 1 and 2, is distinguished by densely packed granule cells and is much thinner (1, 2, 7, 8).

In 1908, Brodmann (7) reported mean cortical thickness measurements of 3.94 mm and 1.86 mm for motor and sensory cortices, respectively, in autopsy specimens. Von Economo and Koskinas in 1925 (8) reported similar measurements of 3.75 and 1.82 mm for motor and sensory cortices, respectively. The central sulcus is the only sulcus in the brain in which the difference of thickness between the two banks is this large. Our purpose was to determine whether this architectonic feature could be identified on MR images. Furthermore, we used scans in the axial plane, since they are perpendicular to most parts of the precentral and postcentral sulci, and therefore provide the most accurate determination of full cortical thickness in these areas. This difference in cortical thickness across the banks of the central

sulcus forms the basis for our direct location of the central sulcus using MR pulse sequences that maximize tissue contrast between gray and white matter.

On T1-weighted sequences, MR imaging can distinguish gray matter from white matter because of fundamental differences in the structure of these tissues and the mobility of their water content. The cortical gray matter contains numerous neurons and neuroglia. These cells have a high cytoplasmic water content in the perikaryal region. Perikaryal water molecules in neurons and glia provide a major contribution to the protons that generate the MR signal of gray matter. In contrast, the majority of the water in myelinated white matter is within axons, which are ensheathed in myelin (9, 10). A superficial layer of extracellular water isolates the axon and its plasma membrane from the myelin sheath. The myelin sheath consists of spiral wrappings of specialized oligodendroglial cells composed of approximately a dozen layers of a repeating sequence of lipid-cytoplasm-lipid-extracellular fluid, with an overall water content of approximately 40% (9, 10).

At 1.5 T, the T1 relaxation time of white matter (510 milliseconds) is shorter than that of gray matter (760 milliseconds) (11). Experimental data suggest that neither the lipid protons within myelin nor the water fraction of myelin contributes directly to the signal characteristics of white matter (9, 10, 12). Lipid-bound water in myelin shortens the T1 relax-

ation time of axoplasmic unbound water by a magnetization transfer effect (9, 10, 13). Although Koenig and others (9, 10) implicated cholesterol as the key determinant of the magnetization transfer effect responsible for T1 shortening of white matter, recent experimental work by Kucharczyk et al (13) suggests that cerebroside has a stronger effect than phosphatidylcholine, cholesterol, and sphingomyelin. This interaction between the lipid-bound water of myelin and cytoplasmic water is, in part, responsible for the relatively shorter T1 relaxation time of white matter compared with gray matter on conventional T1-weighted images.

Inversion-recovery MR imaging accentuates the differences between gray and white matter and allows for a more precise identification of gray matter boundaries in the cerebral cortex (11, 14). The turbo-IR pulse sequence used in this study begins with a 180° inversion pulse before image acquisition in order to generate heavily T1-weighted images. After inversion, the spins relax (recover) in an exponential fashion, characterized by the T1 of the tissue examined. A turbo spin-echo pulse sequence is applied after a delay (inversion time of 300) in order to generate signal for imaging. The combination of an IR prepulse with a turbo spin-echo sequence allows for a high (512) matrix acquisition with a good signal-to-noise ratio in an acceptable imaging time (5 minutes). Tissues with a short T1 will recover longitudinal magnetization rapidly, and therefore generate a large signal. Tissues with a long T1 will recover more slowly and have less longitudinal magnetization available for imaging, therefore generating less signal. The value of IR for providing anatomic detail was recently shown by Achten et al (14), who identified T1 IR as part of an optimum protocol in the evaluation of anatomic alterations associated with temporal lobe epilepsy. Because of the strong gray-white matter differentiation, this method provided excellent visibility of the hippocampal microanatomy. In this study, T1 IR was more sensitive than T2-weighted images for detection of minimal volume loss of the hippocampal formation associated with mesial temporal sclerosis.

The difference in gray matter thickness across the central sulcus corresponds well with known cytoarchitectonic relationships for primary motor and somatosensory cortices (1, 2, 7, 8). The mean cortical thickness measurements for the anterior bank of the central sulcus

(2.70 mm) were significantly ($P < .0001$) larger than for the posterior bank (1.76 mm). In our study, we found that the motor cortex was approximately 1.5 times thicker than the primary somatosensory cortex, a ratio that is close to the ratio of approximately 2 that was reported on autopsy specimens by Brodmann and by von Economo and Koskinas. None of the other adjacent sulci that we examined displayed such a difference of cortical thickness from one bank to the other.

The difference of cortical thickness across the banks of the central sulcus is so pronounced that it can be readily identified by direct visual inspection. These findings provide a direct method for reliably locating the central sulcus in healthy volunteers with the use of IR MR imaging in the axial plane. Further study of mean cortical thickness ratios will be necessary to determine whether our method is equally useful for locating the central sulcus in the diseased state, or perhaps for anatomically confirming such conditions as amyotrophic lateral sclerosis. In practice, it is probably best to understand and apply a variety of anatomic methods to locating the central sulcus in individual patients, because disease processes may obscure sulcal landmarks or gray-white matter differentiation, rendering one method less reliable than others.

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