The central sulcal vein: a landmark for identification of the central sulcus using functional magnetic resonance imaging

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The authors evaluated the anatomical location of the central sulcus (CS) in 24 cerebral hemispheres (eight in which tumors were located centrally, 16 in controls) using: 1) classic anatomical landmarks seen on magnetic resonance (MR) imaging (24 hemispheres); 2) functional MR imaging (24 hemispheres); and 3) intraoperative electrical stimulation mapping (eight hemispheres). On MR imaging the CS was identified with certainty in 79% of hemispheres (four of eight in patients, 15 of 16 in controls). Functional MR imaging identified a parenchymal "motor hand area" in only 83% (20 of 24 hemispheres; five of eight in patients, 15 of 16 in controls); this area was located in the precentral gyrus in 16 (80%) of 20, additionally in the postcentral gyrus in 10 (50%) of 20, and exclusively in the postcentral gyrus in four (20%) of 20. In contrast, functional MR imaging detected one to three sulcal veins presumably draining blood from the adjacent motor hand area in 100% (24 of 24) of the hemispheres studied, and anatomical MR imaging and intraoperative mapping localized these veins in the CS. It is concluded that sulcal veins lying deep within the CS: 1) drain activated blood from the adjacent pre- or postcentral cortex during performance of a motor hand task; 2) can be identified easily with functional MR imaging; and 3) are an anatomical landmark for noninvasive identification of the CS, and thus the sensorimotor strip. The detection of these veins provides a more consistent landmark than the detection of parenchymal motor areas by functional MR imaging; this technique may be used when classic anatomical landmarks fail to identify the sensorimotor strip.

Key Words * motor cortex * functional magnetic resonance imaging * surgery * glioma

The central sulcus (CS) is one of the most important anatomical landmarks of the cerebral cortex. Its significance lies in its proximity to the pre- and postcentral gyri, which contain structures responsible for motor and sensory control.[6,19,20] Most other anatomical landmarks in the brain are described in relation to the CS, which must be defined first when a functional representation, an anatomical landmark, or a pathological entity needs to be localized anatomically. Exact and correct localization of the CS is

therefore crucial.

Several anatomical methods based on imaging modalities such as computerized tomography (CT) or magnetic resonance (MR) imaging have been established to detect the CS and are being refined further. In all of them the CS is defined in relation to other anatomical structures, assuming that these landmarks can be identified reliably.[13,17,18,23] However, a recent study showed that interobserver agreement was at best 76%,[23] revealing the need for further improvement of existing methods or the application of new techniques.

Functional MR imaging is a technique that allows the visualization of local changes in blood oxygenation, changes that are time correlated with a specific task. The validity of functional MR imaging has been established by comparing its results with those obtained by intraoperative electrophysiological mapping of the motor strip,[12,29] namely the "motor hand area" in humans.[29] The motor hand area was found to be located in the precentral gyrus in most individuals, although in some it extended to, or was located exclusively in, the postcentral gyrus.[29] To improve the detection of the CS, we evaluated the feasibility, accuracy, and usefulness of adding a functional method, functional MR imaging, to established anatomical methods.

Clinical Material and Methods

Study Participants

A total of 24 cerebral hemispheres were studied prospectively in eight patients and 11 healthy volunteers (nine women and 10 men; mean age 36.3 years, range 23-62 years). Patients had space-occupying lesions that were located close to or in the precentral gyrus in the language-dominant (five patients) or nondominant (three patients) hemisphere, and functional MR images were obtained in their affected hemispheres. Intraoperative cortical mapping was performed before tumor removal. In the volunteers, eight right and eight left hemispheres were investigated with functional MR imaging; five of these volunteers were tested bilaterally. All volunteers were right-handed according to the Edinburgh inventory test for handedness.[18]

Magnetic Resonance Imaging

Anatomical Imaging. Imaging was performed with a 1.5-tesla magnet (Magnetom SP 63/Vision; Siemens AG, Erlangen, Germany). We evaluated the lesion and its anatomical location by T1- and T2-weighted sequences and by a three-dimensional fast low-angle shot sequence (radiofrequency spoiled, repetition time (TR)/echo time (TE) = 15/6 msec, flip angle = 20, field of view = 200, matrix = 256 x 256) or a magnetized prepared rapid acquisition gradient echo (MPRAGE) sequence (TR/TE = 12/4.4 msec, temporal average = 13.38 minutes, acquisition = 1, field of view = 250 x 250, matrix = 256 x 256).

Functional MR Imaging. A two-dimensional fast low-angle shot sequence was used in a single-slice technique (radiofrequency spoiled, TR/TE = 46.75/30 msec, flip angle = 40, field of view = 200, matrix = 128 x 256). For each slice 27 measurements were acquired, with each measurement lasting 6 seconds.[8,29] The total examination time for each slice was therefore 2.43 minutes. Eleven measurements were obtained before, six during, and 10 after the participants performed a motor task.[8,29] The motor task consisted of repetitive opening and closing of the fist at a frequency of approximately two times per second, a task that can also be performed by patients whose control of fine movements is disturbed. To study the area between the vertex and the corpus callosum, nine to 13 contiguous 4-mm slices were obtained parallel to the bicommissural line.[9,29] The head position of the

participant was fixed by means of a head coil.

Data Analysis

Anatomical MR Imaging. The CS was localized on anatomical MR images using two methods: the lateral and medial axial methods. Using the lateral axial method, the superior frontal sulcus is identified first. This sulcus forms a right angle with the precentral sulcus, which is identified next. The sulcus just behind the precentral sulcus is the CS.[13,23] Using the medial axial method,[23] the marginal ramus of the cingulate sulcus is identified first. The sulcus located anterior to it is the CS. To indicate the degree of difficulty in identifying the CS, we developed a simple scoring system according to which a structure received a score of 0 if it could not be identified, a score of 1 if identification was probable, or 2 if identification was certain. The structures thus evaluated were the superior frontal sulcus/gyrus, the precentral sulcus/gyrus, the marginal ramus of the cingulate sulcus, and the CS.

Functional MR Imaging. Six pretask images and six task images were summed for each slice; the former sum was then subtracted from the latter. On this subtracted image the signal intensities of all bright areas for each of the 27 measurements were plotted in relation to time using a manufacturer-provided software program.[9,29] All the areas with a signal intensity change that corresponded in time to the beginning and end of the task were further evaluated. The significance of these changes was assessed using the Mann-Whitney U-test.[28] To detect motion artifacts, consecutive images from each section were examined in cine mode to detect possible motion of the head; summed images were examined for blurred margins, and subtracted images were examined for the presence of anatomical structures that would appear as a result of incongruencies in the summed images.

Correlation of Anatomical and Functional MR Imaging Results. Whenever possible the precentral gyrus and the CS were identified first in each participant. Next, the areas determined by functional MR imaging to have a significant change in signal intensity were superimposed on that participant's anatomical MR image. The anatomical locations of the areas of high signal intensity on functional MR imaging were then recorded on the participant's anatomical MR images.[9,29]

Intraoperative Mapping

Evaluation of Cortical Stimulation Results and Anatomical Localization. The technique we used for intraoperative stimulation and observation of motor responses[6,19,20] in the contralateral limbs and face has been described previously.[21] The CS was defined using the results of cortical mapping of motor face, hand, and foot representation in conjunction with the same anatomical landmarks used for MR imaging.

Comparison of MR Imaging, Functional MR Imaging, and Intraoperative Mapping. In patients the shape and location of the precentral gyrus as defined intraoperatively were compared with the shape and location of this area visualized on anatomical MR images. Then the maps obtained using functional MR imaging were superimposed on the patient's anatomical MR image, and the exact locations of functional areas were recorded on the anatomical MR image.

Results

Magnetic Resonance Imaging

TABLE 1
CLINICAL AND RADIOLOGICAL FINDINGS IN 11 VOLUNTEERS AND EIGHT PATIENTS UNDERGOING
LOCALIZATION OF THE CENTRAL SULCUS*

Clinical Data					Radiological Data												
Case No.	Age (yrs), Sex	Diagnosis		Side†		Landmarks on MRI (score)							fMRI				
		Histo-logy	Loca-tion	Rt	Lt	SFS	PrCS	SFG	PrCG	MRCs	CS	PA (score)	Loca-tion	No.	SI	ΔInt(%)	
patient																	
1	46, F	cav	PCG	1		2	2	2	2	2	2	2	CS	1	3	5	
2‡	34, F	cav	MFG	1		2	0	2	1	2	1	2	CS	1	5	3	
3	25, F	cav	PCG		1	2	2	2	2	2	2	2	CS§	1	3	5	
4	26, F	glio	MFG		1	0	1	2	1	2	1	2	CS§	1	5	9	
5	43, F	glio	SFG		1	1	1	2	1	2	2	2	CS	1	2	5	
6	44, M	glio	PrCG		1	2	1	2	1	0	1	0	CS	1	3	12	
7	51, M	glio	SFG		1	0	0	0	0	1	0	0	CS	1	3	8	
8	55, F	glio	PrCG	1		2	2	2	2	2	2	0	CS	1	6	19	
volunteer																	
9	37, F	NA	NA		1	2	0	2	2	2	2	0	CS	1	6	11	
10	23, F	NA	NA	1		0	0	2	2	2	2	2	CS	1	5	4	
11	62, M	NA	NA		1	2	2	2	2	2	2	2	CS	1	4	4	
12	28, M	NA	NA		1	1	0	2	1	2	1	2	CS	2	6	8	
13	25, M	NA	NA	1		1	2	2	2	2	2	2	CS	1	1	6	
14	23, M	NA	NA	1		1	2	2	2	2	2	2	CS	2	4	6	
15	36, M	NA	NA	1		1	1	2	2	2	2	2	CS	2	4	4	
					1	2	2	2	2	2	2	2	CS	1	4	4	
16	25, M	NA	NA	1		1	2	2	2	2	2	2	CS	1	6	2	
					1	2	1	2	2	2	2	2	CS	1	5	3	
17	40, M	NA	NA		1	2	2	2	2	2	2	2	CS§	2	5	12	
				1		2	2	2	2	2	2	2	CS	2	6	9	
18	34, M	NA	NA		1	2	2	2	2	2	2	2	CS	1	5	7	
				1		2	2	2	2	2	2	2	CS§	2	5	7	
19	33, F	NA	NA	1		2	0	2	2	2	2	2	CS	2	7	4	
					1	2	1	2	2	2	2	2	CS	3	6	4	
total hemispheres				11	13	24	24	24	24	24	24	24		24	24	24	
average signal intensity increase (%)						1.5	1.3	1.9	1.7	1.9	1.8	1.7		1.4	4.5	6.7	

* The scoring system gives the certainty at which a given structure could be identified on MR imaging: 0 = not identified; 1 = identification probable; 2 = identification certain. Abbreviations: Δ Int(%) = intensity increase in percent of baseline before task movement (range 2%–19%); Act SVs = activated sulcal veins; cav = cavemoma; CS = central sulcus; glio = glioma; fMRI = functional magnetic resonance imaging; MFG = middle frontal gyrus; MRCs = marginal ramus of the cingulate sulcus; MRI = magnetic resonance imaging; PA = parenchyma activated; PCG = postcentral gyrus; PrCG = precentral gyrus; PrCS = precentral sulcus; SFG = superior frontal gyrus; SFS = superior frontal sulcus; SI = slices; surf = lateral surface.

† Affected hemisphere tested in patients.

‡ All p values according to the Mann–Whitney U-test were ≤ 0.001, except in Case 2 (p ≤ 0.01).

§ Veins were detected in the CS and in the post-CS.

Anatomical MR Imaging Data Analysis. The CS could be identified with certainty (score 2) in 19 of 24 hemispheres (four of eight patients, 15 of 16 of volunteers, (Table 1). The definition of the CS was difficult (score 1) in four of 24 hemispheres (three of eight patients, one of 16 of volunteers) and was not possible (score 0) in one hemisphere (one of eight patients, Case 7). The mean scores for certainty of identification of the CS were 1.95 for the volunteers and 1.4 for the patients (Table 2). Individual identification scores for the sulci and gyri are noted in Table 1.

TABLE 2
COMPARISON OF RADIOLOGICAL FINDINGS IN 11 VOLUNTEERS (16 HEMISPHERES) AND
EIGHT PATIENTS (EIGHT HEMISPHERES)*

Parameter	Landmarks on MR Imaging												Functional MR Imaging								p Value
	SFS		PrCS		SFG		PrCG		MRCS		CS		Paren- chyma		Veins (no.)		Δ Intensity (veins, %)				
	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt	Vol	Pt			
mean identification																					
score†	1.6	1.4	1.3	1.1	2	1.8	1.9	1.3	2	1.6	1.9	1.4	1.9	1.3	1.6	1	5.9	8.3	>0.1		
min	0	0	0	0	2	0	1	0	2	0	1	0	0	0	1	1	2	3			
max	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	1	12	19			
* CS = central sulcus; max = maximum; min = minimum; MR = magnetic resonance; MRCS = marginal ramus of the cingulate sulcus; pt = patients in Cases 1 to 8 in Table 1; PrCG = precentral gyrus; PrCS = precentral sulcus; SFG = superior frontal gyrus; SFS = superior frontal sulcus; Vol = volunteers 9 to 19 in Table 1.																					
† The scoring system gives the certainty at which a given structure could be identified on MR imaging: 0 = not identified; 1 = identification probable; 2 = identification certain.																					

Functional MR Imaging Data Analysis. In 15 of 16 hemispheres in volunteers (Fig. 1) and in five of eight hemispheres in patients (Figs. 2 and 3) a localized, significant (p less than or equal to 0.001, U-test) task-related increase in signal intensity of 1.5% to 9% was found that projected into the brain parenchyma in the central region contralateral to the task movement. This area was defined as the "motor hand area." In the remaining four hemispheres examined, no such motor hand area could be detected in the brain parenchyma.

Fig. 1. Case 17. a: Functional magnetic resonance (MR) image showing the parenchymal motor hand area located in the pre- and postcentral gyrus in a normal volunteer. b: Graph showing that the increase and decrease of signal intensity in this motor hand area was statistically significant (p equal to or less than 0.001, Mann-Whitney U-test) and coincided with the beginning and end of the motor task (repetitive opening and closing of the contralateral hand). c: Functional MR imaging slice located superior to that seen in (a)

showing two veins located in the central sulcus; they presumably drain activated blood from the pre- and postcentral gyri (parenchymal motor hand area in (a)). d: Graph showing similar results to those shown in (b); the increase and decrease of signal intensity in this vein was statistically significant (p less than or equal to 0.001, U-test) and coincided with the beginning and end of the motor task.

In all 24 of the hemispheres examined a spotlike structure was detected (Figs. 1c, 2b-f, and 3b-d). Its signal intensity change was 4.5% (range 2%-19%) of baseline, coincided with the beginning and the end of the motor task, and was statistically significant (p less than or equal to 0.001) (Figs. 1d and 2e). The same spot was visible on adjacent superior slices, and in many instances it could be seen on slices as far above as the vertex. In one patient, we could show that after administration of gadolinium-diethylenetriamine pentaacetic acid (Gd-DTPA), this spot clearly enhanced (Case 8, Fig. 3b-f). We therefore judged that this spot seen on single slices, which corresponded to a tubular structure seen when evaluating serial slices, must represent a blood vessel, most probably a vein.

Fig. 2. Case 7. a: A T1-weighted magnetization prepared rapid acquisition gradient echo

(MPRAGE) image of a recurrent left frontal oligodendroglioma with hemorrhages. The central sulcus (CS) cannot be localized using classic anatomical landmarks. b: Summed functional MR image obtained in the patient at rest, in which the vein is hypointense (arrow). c: Summed functional magnetic resonance (MR) image obtained during motor activation of the contralateral hand, in which the vein is hyperintense (arrow). d: Subtracted image (c minus b) showing several hyperintense areas highlighted with circles. AH = anterior, head; V = sulcal vein; 1, 2, and 3 = parenchymal areas. e: Graph analyzing the time course of signal intensity changes. In the parenchymal areas 1 to 3 (P1-3) no task-correlated changes were observed, whereas increase and decrease of signal intensity in the vein (designated by *arrows* in b and c; V in d) was statistically significant (p less than or equal to 0.001, Mann-Whitney U-test) and coincided with the beginning and end of the motor task. f: A T1-weighted MPRAGE image showing the sulcal vein to be located immediately behind the gyrus next to the tumor. g: Postoperative T1-weighted proton density image showing complete gross-total resection of the tumor that was located in the frontal gyri immediately anterior to the precentral gyrus, according to intraoperative mapping. The CS and the postcentral gyrus (with a lateral fork-shaped appearance visible in f) are now decompressed and back to their regular shape.

Correlation of Anatomical and Functional MR Imaging Results. The parenchymal area that corresponded to the motor hand area was located in the precentral gyrus in 16 hemispheres (in 12 volunteers and four patients), additionally in the postcentral gyrus (Fig. 1a) in 10 (in eight volunteers and two patients); and exclusively in the postcentral gyrus in four hemispheres (in three volunteers and one patient). Independently of whether a parenchymal motor hand area was visible or not, at least one vein was always located deep in the middle part of the CS (Figs. 1c, 2f, and 3b-f), in proximity to the motor hand area when this was identifiable. These CS veins varied in number from one (17 hemispheres), to two (six hemispheres), to three (one hemisphere). When multiple veins were present they usually merged into one vein on superior slices. These veins could be followed for up to seven adjacent slices (mean 4.7).

Fig. 3. Case 8. a: A T2-weighted magnetic resonance (MR) image showing a recurrent left frontal glioma. The central sulcus is well identified. b: Summed functional MR image obtained in the patient at rest showing a slice superior to that seen in (a). The sulcal vein is hypointense (arrow). c: Summed functional MR image obtained during motor activation of the patient's contralateral hand, in which the vein is hyperintense (arrow). d: Subtracted image (c minus b) showing the hyperintense vein (circle). e: A T1-weighted MR image from the same slice position as b, c, and d. f: Contrast enhanced T1-weighted MR image (same slice position as in e). The same structure as in b, c, and d shows enhancement, thereby proving to be a vein (arrow). g: Contrast enhanced T1-weighted MR image of a slice positioned superior to e and f, showing drainage of the vein into a bridging vein (arrow).

In two patients an additional vein was identified in the postcentral sulcus close to the surface of the brain, rather than in the middle segment and deep within the sulcus where the CS veins lie. One of these patients had a cavernoma in the postcentral gyrus, which might have contributed to rerouting of venous drainage. The second patient had an astrocytoma in the middle frontal gyrus and a parenchymal area that was much more lateral than usual, probably as a result of cortical reorganization. In both instances these additional veins (superficial and lateral) could not be confused with the CS vein.

Intraoperative Mapping

Evaluation of Cortical Stimulation Results and Anatomical Localization. In all eight patients, direct cortical stimulation evoked a contralateral motor response in the small hand muscles and additionally in the arm and leg or in the face. Using these data with the anatomical landmarks, the precentral gyrus could always be identified with certainty.

Comparison of Functional MR Imaging, MR Imaging, and Intraoperative Mapping Results. In the five patients in whom a parenchymal motor hand area was detected with functional MR imaging, the location of the precentral gyrus defined by intraoperative mapping corresponded to the location indicated by functional MR imaging/MR imaging results; details of the measurements in these five patients have been published elsewhere.[29] The sulcal vein identified by functional MR imaging was therefore located in the CS. The following case reports describe findings in two of the three patients in whom no parenchymal motor hand area was identified by functional MR imaging.

ILLUSTRATIVE CASES

Case 7

This 51-year-old man (Table 1) suffered from a recurrence of a left frontal low-grade astrocytoma and weakness in his right hand.

Examination. On MR imaging (Fig. 2a) the anatomy of the cortical surface was so distorted that the CS could not be localized using the axial method (score 0 for all anatomical structures). Using the lateral sagittal method,[17,18] it was our impression that the precentral gyrus could correspond to the gyrus that was immediately posteriorly adjacent to the tumor, although the distorted anatomy prevented a definitive statement. On functional MR imaging no motor hand area could be detected in the parenchyma. On three adjacent slices, however, a hyperintense spot was seen that was considered to represent a vein (Fig. 2d and e). By superimposing the results of the functional MR imaging on anatomical MR images (Fig. 2f), this spot was found to project into a sulcus in the central region and was thus considered to correspond to

a sulcal vein (see *Discussion*). On the basis of our previous findings, we concluded that this should be the CS; that is, the sulcus in which the vein was seen was the first sulcus identified posterior to the tumor. The precentral sulcus was obliterated, and no sharp boundary existed between the tumor and the precentral gyrus.

Operation. During surgery, motor responses were elicited from sites that were located anterior to the first visible sulcus and immediately posterior to the tumor. As mentioned, this location had been predicted by functional MR imaging to be the precentral gyrus (Fig. 2a and f); thus intraoperative mapping confirmed the results of functional MR imaging. Furthermore, these findings indicated that the tumor, which had been considered inoperable by other surgeons because the relationship between the tumor and the motor strip was unclear, could be resected without postoperative deficit (Fig. 2g).

Case 8

This 55-year-old woman (Table 1) suffered from a recurrence of a right-sided low-grade astrocytoma.

Examination. On MR imaging (Fig. 3a) the anatomy of the cortical surface was easily identified despite postoperative changes (score 2 for all anatomical structures), and the tumor was found to be located in the precentral gyrus. On functional MR imaging no motor hand area could be detected in the parenchyma. On six adjacent slices a hyperintense spot was seen in the CS that was considered to represent a sulcal vein (see *Discussion* and Fig. 3b-d). After administration of Gd-DTPA, this vein clearly enhanced (Fig. 3e and f) and joined a bridging vein seen on a superior slice (Fig. 3g).

Operation. During surgery, motor responses were elicited from the precentral gyrus as defined by MR imaging and functional MR imaging, confirming the results of these studies.

Discussion

Activation of Parenchyma Using Functional MR Imaging

Earlier studies[7] have shown that activation of a certain area of the cerebral cortex causes an increase in regional blood perfusion in this area. This leads to a decrease in the blood concentration of deoxyhemoglobin, which in turn causes an increase in signal intensity in the activated area on functional MR imaging. Previous studies have shown that, among others, the motor hand area can be detected on functional MR imaging and localized to the parenchyma of the precentral gyrus.[12,29] Moreover, morphometric coordinates of motor hand areas found by using functional MR imaging and by intraoperative mapping of the exposed sensorimotor strip were identical, thus validating the results of functional MR imaging.[29] Currently it is assumed that changes in smaller intraparenchymal veins or venules account for this increased signal intensity[14,15] in the parenchyma.

In the present study we could identify the parenchymal motor hand area using functional MR imaging in 20 (83%) of the 24 hemispheres examined (five of eight hemispheres in patients affected by space-occupying lesions, and 15 of 16 hemispheres in the 11 volunteers). This parenchymal area was most often located in the posterior bank of the precentral gyrus (16 (80%) of 20 hemispheres), but it was seen additionally in the postcentral gyrus in 10 (50%) of 20 hemispheres (Fig. 1a) or exclusively in four (20%) of 20 hemispheres. Two explanations can be offered for this increased perfusion in the postcentral gyrus. First, sensory reafferences that terminate in the postcentral gyrus may be activated with motor activation.[10] Second, pyramidal cells may be found in the postcentral gyrus, and these cells contribute to motor activation;[3] this has been observed by others, who demonstrated that direct electrical

stimulation of the postcentral "sensory" cortex can also elicit motor responses in the contralateral skeletal muscles.[19,20,26] Such interference, however, makes identification of the precentral gyrus by locating the motor hand area with functional MR imaging less reliable.

Activation of Sulcal Veins Using Functional MR Imaging

The most consistent finding in the present study was the appearance on functional MR imaging of one or more high-intensity spots that were located deep within a sulcus (Figs. 1c, 2f, and 3b-f). These spots had significant increases in signal intensity, the increases coincided with the beginning and end of the motor task (Figs. 1d and 2e) and had a pattern of signal intensity change similar to that observed in the parenchymal motor hand area (Fig. 1b). These sulcal spots were visible in several slices superior to the parenchymal motor hand area in all cases in the present study. Because these spots were contiguous on the adjacent slices, they can only correspond to tubular structures, that is, vessels. Because task-related changes in deoxyhemoglobin concentration as well as inflow effects are only observed in the venous system,[1,2,4,7,8,11,14,22] we assume that these vessels correspond to sulcal veins. This assumption was confirmed in the patient in Case 8, in whom we could demonstrate that the CS vein defined by functional MR imaging enhanced after administration of Gd-DTPA and drained into a bridging vein (Fig. 3f). Moreover, just recently functional MR imaging was used successfully to perform venous MR angiography.[1,2] The gold standard to prove our assumption that the above-mentioned spots correspond to veins would be to perform functional MR imaging and MR angiography in the same session. Our prospective examination protocol, however, included digital subtraction (DS) angiography rather than MR angiography. Because of the different imaging planes (lateral and anteroposterior for DS angiography, axial for functional MR imaging) and the lack of a common reference system for DS angiography and functional MR imaging, DS angiography cannot be used currently to validate functional MR imaging.

It should also be emphasized that these veins are not superficial structures but are found deep in the middle part of the CS on MR imaging; therefore, they cannot be detected by inspecting the cortical surface during surgery, for example.

Venous Drainage of Activated Parenchyma

There has been a debate about whether the anatomical correlate of increased signal intensity detected by functional MR imaging consists of veins or venules.[4,8,11,14,15,22] Our results, at least in those cases in which we found activation in parenchymal and sulcal structures simultaneously, show that either hypothesis is true. Venules give rise to increased signal intensity in the parenchyma, whereas the larger veins that drain this area are located in the adjacent CS.

It seems reasonable to assume that the sulcal veins just described are fed by smaller veins or venules within the cortex of the adjacent anterior and posterior banks of the pre- and postcentral gyri, respectively.[22] If so, the veins would also drain the motor hand area independent of the location of this area in the precentral or postcentral gyrus or in both. Venous drainage of this area would then lead to a decrease in the concentration of deoxyhemoglobin that would be reflected as an increase in signal intensity in sulcal veins on functional MR imaging, an increase that would also correspond in time with the beginning and end of a motor task. Signal intensity would return to normal as the concentration of deoxyhemoglobin in the veins was normalized by dilution. Alternative interpretations for these task-related changes in signal intensity of veins would be direct inflow effects or a combination of deoxygenation and inflow effects.[4]

The CS veins that were localized by functional MR imaging in this study drain the motor hand area. The veins and the parenchymal motor hand area thus evidence changes in MR imaging signal intensity when the motor task is performed. However, whereas the veins were consistently seen to be located in the CS, the parenchymal motor hand area showed an important degree of variability in location, and this area could not be detected in 17% of the cerebral hemispheres examined (mainly in patients with space-occupying lesions compressing the central region). The CS veins thus proved to be a far more stable landmark than the parenchymal motor hand area found with functional MR imaging.

Methodological Considerations

The methods of off-line statistical analysis that we[29] and others[8,9,11,12,14,15] used for functional MR imaging was designed to make visible those signal changes that coincide in time with the beginning and end of the motor task. Our study suggests that these changes took place in the primary sensorimotor strip exclusively. On the other hand, physiological phenomena preceding or succeeding these phenomena and taking place in other areas (for example, the premotor or supplementary motor area or the ipsilateral hemisphere) have not been visualized with this technique. Furthermore, taking into account the signal-to-noise ratio, time, and spatial resolution characteristics of the blood oxygenation level-dependent technique when using a 1.5-tesla imager, subtle changes possibly occurring in areas outside the primary sensorimotor strip may have remained undetected. However, increasing the sensitivity by changing the technique of data acquisition or the off-line statistical analysis would lead to the identification of parenchymal areas or veins outside the primary sensorimotor strip. This would decrease the specificity of our method, which was designed to define structures in the primary sensorimotor strip. It should also be noted that the subtraction technique, which is the first step in our off-line statistical analysis, revealed a variable number of hyperintense areas beyond the CS vein (Fig. 2d). Therefore, in the second step all hyperintense areas were submitted to a statistical analysis to decide which of them resulted from a task-related change in signal intensity (Fig. 2e). Only the CS veins revealed signal intensity changes that were time correlated with the task. Changes found in the other hyperintense areas were attributed to nonspecific flow effects or artifacts. This second step is therefore crucial to reliable identification of the CS vein.

Techniques for Localization of the Central Sulcus

On conventional (anatomical) MR or CT studies, the CS can be defined indirectly by its location with respect to cortical (superficial) or commissural (deep) landmarks. These landmarks are usually easily identifiable in normal brains. In contrast, independently of whether the lateral axial,[13] medial axial,[21] lateral sagittal,[17,18] or the midline sagittal[5,16,24] method is used to define the CS, the inherent problem when using cortical landmarks is that the variability of sulci and gyri can complicate the identification of the CS considerably. This probably accounts for the notable differences in interrater reliability calculated by Sobel, *et al.*, [23] for various methods. Since the paper by Sobel, *et al.*, which is the only report in which different methods for the identification of the CS were compared, an improved lateral sagittal method has been described. Although this new method was found to have greater than 90% accuracy in normal brains,[17] it has not yet been used to study brains affected by a space-occupying lesion.

Another method for identifying the CS is to use a defined reference system[27] such as that presented in the atlas by Talairach and Tournoux.[25] The usefulness of such systems rests on the consistency of anatomical landmarks deep in the cerebral hemispheres (the anterior and posterior commissures) and the

relation of cerebral structures to these landmarks.

However methods used to identify the CS that rely on locating either cortical[5,13,16,17,24] or deep[25,27] anatomical landmarks may be complicated or made unreliable by the presence of a space-occupying lesion in the central region, as reflected by the lower score (1.4 compared to 1.95) for identification of the CS in patients with tumors compared to healthy volunteers in our study.

CONCLUSIONS

The identification of a central sulcal vein by functional MR imaging is a reliable way to localize the CS anatomically. In the present study, this direct functional method is not affected by variations in anatomy of the gyri or sulci, variations of the normal anatomy, or tumor-induced distortions of the cortical surface.

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