

Pars triangularis asymmetry and language dominance

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ABSTRACT The pars triangularis is a portion of Broca's area. The convolutions that form the inferior and caudal extent of the pars triangularis include the anterior horizontal and anterior ascending rami of the sylvian fissure, respectively. To learn if there are anatomic asymmetries of the pars triangularis, these convolutions were measured on volumetric magnetic resonance imaging scans of 11 patients who had undergone selective hemispheric anesthesia (Wada testing) to determine hemispheric speech and language lateralization. Of the 10 patients with language lateralized to the left hemisphere, 9 had a leftward asymmetry of the pars triangularis. The 1 patient with language lateralized to the right hemisphere had a significant rightward asymmetry of the pars triangularis. Our data suggest that asymmetries of the pars triangularis may be related to speech–language lateralization.

Paul Broca (1) described eight right-handed patients who lost the facility of speech and were found to have left hemispheric lesions. Broca (1) thought that the left third frontal convolution, including pars triangularis, was critical for speech. Although subsequent studies have demonstrated that left-sided lesions restricted to the third frontal convolution are probably associated with only transient loss of speech (2, 3) lesions of the right third frontal convolution rarely produce any speech deficits. These observations suggest that although the left inferior frontal lobe appears to be important in speech production, other undamaged areas can either compensate or substitute for this area. Both cortical stimulation (4, 5) and functional imaging studies (6–9) have provided support for the role of the left inferior frontal lobe in speech production. Wernicke (10) demonstrated that a lesion in the posterior portion of the left superior temporal lobe produced a syndrome different from that described by Broca (1). Whereas Broca's patients lost the capacity to speak fluently but retained comprehension, Wernicke's patients retained the ability to speak fluently but were impaired at comprehending speech. Subsequently, morphological cerebral asymmetries in the posterior superior temporal speech region (planum temporale) were demonstrated on postmortem brains (11–15), with a predominant leftward asymmetry of the planum temporale. However, consistent asymmetries of the inferior frontal region have been more difficult to demonstrate on postmortem studies (13, 16–18). Therefore, the distinctive morphological asymmetries of the planum temporale have been thought to be the neuroanatomical substrate for speech and language. Furthermore, the planum temporale constitutes part of cytoarchitectonic areas TA and TB, which are auditory association cortices important in higher order processing of auditory language input. However, direct evidence supporting this structure–function relationship has been lacking.

With the advent of three-dimensional volumetric magnetic resonance imaging (MRI), *in vivo* quantitative analysis of the

planum temporale can be performed (19–22). Given these advances in MRI technology, reliable measures of language laterality and handedness can be evaluated in the same individuals, thus allowing direct structure–function correlations. Using this technique, Steinmetz *et al.* (22) studied planum temporale asymmetries in a group of left- and right-handers. A leftward asymmetry of the planum temporale was documented with a greater degree of leftward asymmetry in the right-handers as compared with the left-handers. Blonder, Pettigrew, and Smith (23) used volumetric MRI to evaluate the relationship between the planum temporale and atypical language dominance in a case study. They found a rightward asymmetry of the planum temporale in their patient who developed a Broca's aphasia following a unilateral right hemispheric stroke, suggesting that asymmetries of the planum temporale may predict language laterality. We recently measured the planum temporale on volumetric MRI scans of patients who had selective hemispheric anesthesia (Wada testing) performed for speech–language lateralization (24). All subjects who had language lateralized to the left hemisphere (11 right-handers) had a leftward asymmetry of the planum temporale. The one subject (non-right-hander) who had language lateralized to the right hemisphere had a strong rightward asymmetry of the planum temporale. These data suggest that planum temporale asymmetries determined by volumetric MRI may predict speech–language laterality and offer support for the notion that the planum temporale plays an important role in speech–language dominance.

Although morphologic asymmetries of the planum temporale have been well established and recent data suggest that these asymmetries may predict laterality of speech–language (24), it has been more difficult to identify a portion of the frontal operculum that can be reliably measured and that may predict laterality of speech–language. Witelson and Kigar (25) reviewed data from studies on asymmetries of the frontal operculum and suggested that there was no evidence that the lateral aspect of the frontal operculum is asymmetric. They proposed, however, that an asymmetry may be present if the intrasulcal cortical surface area of this region was measured. Wada *et al.* (13) measured the surface area of the pars opercularis and posterior portion of the pars triangularis in adult and infant postmortem brains. Although no significant leftward asymmetry was found, Wada and coworkers suggested that the pattern of gyrification of the third frontal convolution was more elaborate in the left hemisphere and that if the depths of the convolution were measured, then a leftward asymmetry would probably be present. Falzi *et al.* (17) measured the depths of the convolution in 12 right-handers and found a leftward asymmetry in 75% and a rightward asymmetry in 25%. In 24 adult postmortem brains Albanese *et al.* (18) found a leftward asymmetry in the posterior portion of

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Abbreviations: MRI, magnetic resonance imaging; AQ, asymmetry quotient; AHR, anterior horizontal ramus; AAR, anterior ascending ramus.

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the frontal operculum. When Albanese *et al.* (18) analyzed discrete portions of the frontal operculum, the most significant leftward asymmetry occurred in the caudal portion of the pars triangularis. The pars opercularis did not show as significant a leftward asymmetry as the caudal portion of the pars triangularis. However, the pars triangularis was not measured in isolation by Albanese *et al.* (18) nor in any other studies that have investigated asymmetries of the frontal operculum. Therefore, there are no data regarding asymmetries of the pars triangularis.

Because asymmetries of the frontal operculum have been more difficult to demonstrate than asymmetries of the planum temporale (13, 16–18) and given the recommendations of Witelson and Kigar (25) regarding measuring the intrasulcal cortical surface area of this region, we developed a method of measuring the pars triangularis on volumetric MRI scans (26). The pars triangularis constitutes a portion of Broca's area (Brodmann's area 45). The pars triangularis is bounded superiorly by the inferior frontal sulcus, inferiorly by the anterior horizontal ramus (AHR), and caudally by the anterior ascending ramus (AAR). Since the AHR and AAR are major branches of the sylvian fissure, they are readily identifiable on sagittal MRI sections; therefore, the depths of these convolutions can be measured and asymmetries of the pars triangularis can be calculated. To learn if there are anatomic asymmetries of the pars triangularis, these convolutions were measured on sagittal volumetric MRI in a group of normal right- and left-handers (26). Results of our study demonstrated that whereas the right-handers had a significant leftward asymmetry of the pars triangularis, the left-handers were more anomalous. All of the right-handers (seven of eight) had a larger left pars triangularis (leftward asymmetry), except one with equal measures. In contrast, four of eight (50%) left-handers had a rightward asymmetry, one (12.5%) had equal measures, and three of eight (37.5%) had a leftward asymmetry. Whereas most right-handers have language lateralized to the left hemisphere, left-handers are more anomalous (27–32). Since the pars triangularis constitutes a portion of Broca's area (Brodmann's area 45), which is important in speech–language production, and because our data suggest that asymmetries of the pars triangularis may be associated with lateralized speech–language functions, further anatomic studies with neurobehavioral correlation of speech–language dominance seemed warranted. Given the behavioral significance of this region in lateralized language functions, and the reliable landmarks that define the inferior and caudal convolutions of the pars triangularis, we measured the depths of these convolutions (AHR, AAR) on volumetric MRI scans of patients who had undergone a Wada procedure for localization of language. We predicted that asymmetries of this portion of the pars triangularis would correlate with language laterality.

METHODS

Subjects. Subjects included consecutive patients evaluated at Shands Hospital, University of Florida, for possible seizure surgery. These patients underwent selective right- and left-hemispheric anesthesia (Wada testing) and a three-dimensional gradient echo volumetric MRI scan. Patients with a childhood language disorder, focal neurological deficits, or abnormalities on MRI scan were excluded. Eleven patients (6 male, 5 female) were studied with a mean age of 32.4 years \pm 11.7 SD and a mean educational level of 11.9 years \pm 1.7 SD. Participants were stringently classified as consistent right-handers or nonconsistent right-handers based on Annett's (33) model of hand preference and similar to the definition of Witelson and Kigar (25). Consistent right-handers performed all 12 items from a handedness inventory (34) with the right hand. Nonconsistent right-handers include individuals with mixed hand preference (performs at least one task with the left hand) or consistent left-handers (left-hand preference on all

12 items). Ten of the subjects were consistent right-handers, and one subject (subject 11) was a nonconsistent (mixed) right-hander. The patients' performance on the Wechsler Adult Intelligence Scale-Revised (35) included a mean verbal intelligence quotient of 85 ± 7.4 SD, performance intelligence quotient of 84.2 ± 9.2 SD, and a full-scale intelligence quotient of 83.2 ± 6.7 SD. Seizure focus was fairly equally distributed between the left and right cerebral hemispheres (right = 6, left = 5), providing a control for the effect of seizure focus (Table 1).

Wada Procedure. The Wada procedure was performed after informed consent was obtained. A 5-Fr catheter was inserted percutaneously via a right femoral artery puncture. A carotid angiogram was performed prior to injection to delineate anomalous vascular anatomy or cross-filling. The ultrashort acting barbiturate methohexital (36) was used in individually determined dosages. The catheter tip was inserted above the level of the common carotid artery bifurcation. Right and left carotid injections were performed selectively. Neuropsychological testing was performed before, during, and after each injection. The patient returned to baseline level of functioning before subsequent injection. Inactivation of the hemisphere considered dominant for language was based on global loss of function (global aphasia or speech arrest) by using a technique similar to that established by Wada and Rasmussen (37).

MRI Scan Acquisition. MRI scans were performed with a quadrature head coil in a Seimens 1-T Magnetom (Iselin, NJ) at the University of Florida Health Science Center, Gainesville. For each participant, a gapless volumetric series of thin sagittal sections was obtained using a 6-min "Turboflash" (MPRage) sequence (38) and a T1-weighted image with the following technical factors: repetition time, 10 ms; echo time, 4 ms; 10-degree flip angle; field of view = 25.5; 160-mm excited volume; 130×256 matrix; 128 partitions, 1.25-mm slice thickness. The sagittal images were transferred over a fiber optics network (Vortech, Dallas) to a Sunview workstation (Sparcstation 2, Sun Microsystems, Mountain View, CA), where programs written in PV-WAVE (Precision Visuals, Boulder, CO) stripped the headers, reduced the data, and put the images into a single file labeled with an identification (blind) number for each scan series. The midline image was identified, and the Talairach and Tournoux proportional grid method (39) was used to ensure that similar regions were measured within and across subjects.

Quantitative Measures of the Pars Triangularis. The surface area of the convolutions formed by the AHR and AAR (Fig. 1) was measured in the left and right cerebral hemispheres of each subject. A mouse-driven computer-guided cursor was used to trace these convolutions in consecutive thin sagittal sections. A mean surface area was computed by using the measurements made on 9 to 11 contiguous images located 35–50 Talairach millimeters lateral to the midline. The sub-

Table 1. Patient demographic data

Subject	Age, yr	Gender*	Education level, yr	Seizure focus†	Age at seizure onset, yr
1	55	F	12	R ^T	10
2	19	F	12	R ^T	2
3	19	M	12	R ^T	15
4	33	M	9	L ^T	14
5	38	F	12	R ^F	3
6	36	M	10	L ^F	2
7	40	F	12	R ^T	12
8	33	M	16	L ^T	25
9	17	M	10	L ^T	9
10	42	F	12	L ^T	12
11	24	M	12	R ^F	2

*F, female; M, male.

†R, right hemisphere; L, left hemisphere; T, temporal; F, frontal.

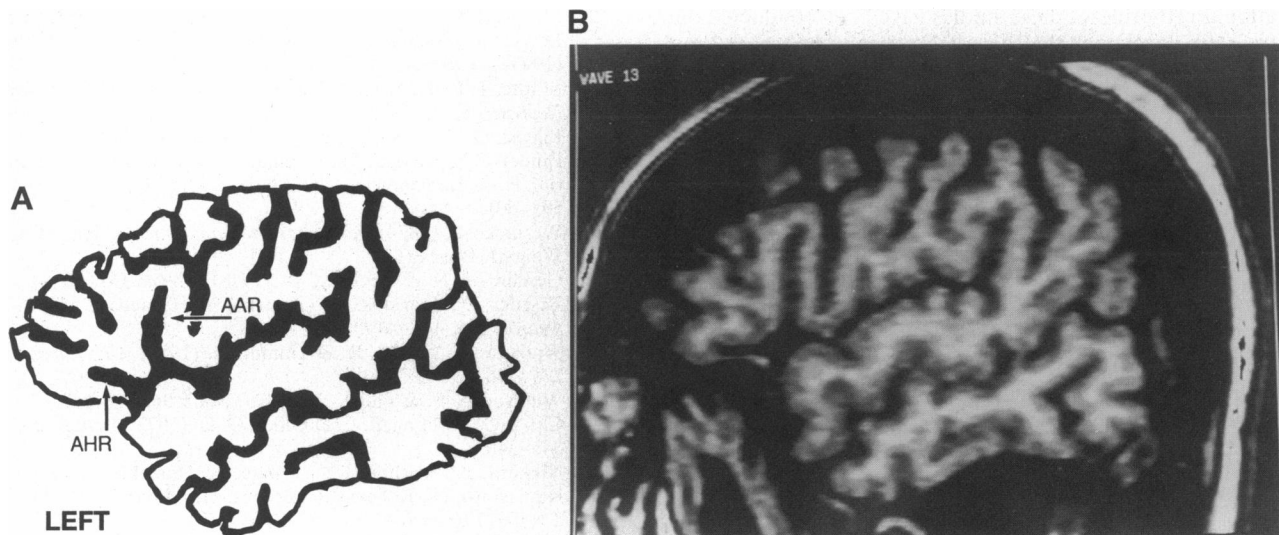


FIG. 1. (A) Anatomical delineation of the pars triangularis on a three-dimensional gradient-echo MRI. (B) A rendering of the image in A shows the AHR and the AAR that define the pars triangularis.

cortical extent of the rami was measured, but the AHR and AAR were not measured on the lateral surface of the brain; therefore, the area measured is an estimate of the total extent of the triangularis convolution. In some cases, the AHR and AAR do not reach the lateral surface of the brain, and the largest portion of the triangular gyrus rarely extends to the lateral surface of the sylvian fissure (40). Furthermore, the AHR and AAR form a triangle when these anterior sulci are well formed; however, when these rami are not as well formed, which occurred in 10% of our sample, it is more difficult to identify these rami. Therefore, a rule-based system was devised to assure reliability in identifying the AHR and AAR. This system was based on the anatomy of the sylvian fissure and anterior branches (40, 41) and used parameters described in recent publications (20, 24, 26). The Talairach and Tournoux (39) coordinate system provided a reliable method to confirm the location of the rami, since within a brain the AHR and AAR in the left and right hemispheres are located at approximately the same x - y coordinates. In at least 90% of the hemispheres measured, including those with reversed asymmetries, the AHR and AAR were easily identified by using anatomical landmarks, and the use of the coordinate system merely confirmed the location of the rami. All MRI measures were performed by two blinded examiners. Each MRI measure was performed twice with good intra-rater and inter-rater reliability (>90%).

RESULTS

Asymmetries of the Pars Triangularis. A paired t test was performed on the mean left and right measures of the pars triangularis (left = $3.17 \text{ cm}^2 \pm 0.77 \text{ SD}$; right = $2.72 \text{ cm}^2 \pm 0.67 \text{ SD}$). There was a significant leftward asymmetry of the pars triangularis ($P < 0.05$). Asymmetry quotients (AQs) were calculated by using the formula: $\text{left} - \text{right}/[(\text{left} + \text{right})(0.5)]$. A similar quotient has been used by others to control for hemisphere size (19, 20, 42). The AQ was considered $L > R$ when the AQ was greater than +0.05 and was considered $R > L$ when the AQ was greater than -0.05. The AQ was equal when $-0.05 > \text{AQ} > +0.05$ (42). A mean AQ was calculated for the pars triangularis (mean AQ = $+0.16 \pm 0.32 \text{ SD}$). Nine of 11 subjects had a $L > R$ pars triangularis (leftward asymmetry), and 2 had $R > L$ pars triangularis (rightward asymmetry).

Results of Wada testing demonstrated that 10 of the 11 subjects (91%) studied had language lateralized to the left cerebral hemisphere, while 1 patient (9%) had language

lateralized to the right hemisphere. Nine of the patients with left hemispheric language dominance had a leftward asymmetry of the pars triangularis. The 1 patient with right hemispheric language dominance had a rightward asymmetry of the pars triangularis (AQ = -0.39). All subjects were consistent right-handers, except one nonconsistent right-hander who had language lateralized to the right hemisphere and had a rightward asymmetry of the pars triangularis.

The planum temporale was previously measured in these cases (24). When a χ^2 test was performed to compare asymmetries of pars triangularis and planum temporale in this sample, there was a significant relationship between these asymmetries ($P < 0.026$). That is, 9 of 11 subjects had a leftward asymmetry of the pars triangularis and planum temporale. All of these 9 subjects had language lateralized to the left hemisphere. The 1 subject with a rightward asymmetry of the pars triangularis and planum temporale had language lateralized to the right hemisphere. One subject had language lateralized to the left hemisphere and had a rightward asymmetry of the pars triangularis and a leftward asymmetry of the planum temporale.

There are limitations to data gathered from a clinical population of seizure patients that need to be addressed. That is, left hemispheric seizure focus may result in a shift of language to the right hemisphere. In our sample there was no relationship between seizure focus and laterality of language. Age of seizure onset may also affect laterality of language, with seizure onset before the age of 10 years resulting in a shift of language to the contralateral hemisphere. Pearson r correlation ($r = 0.097$, $P < 0.78$) revealed no significant relationship between age of seizure onset and laterality of language. Furthermore, there was no significant relationship of seizure focus or age of seizure onset to asymmetry of the pars triangularis.

DISCUSSION

A leftward asymmetry of the planum temporale has been well documented on postmortem specimens (43, 44) and on volumetric MRI scans (19–21). Recent data suggest that morphologic asymmetries of the planum temporale measured on volumetric MRI may predict laterality of language (26). A consistent anatomical asymmetry of the frontal operculum has been more difficult to demonstrate, even though functional asymmetries are more marked anteriorly than posteriorly (13, 16–18). However, previous reports on asymmetries of the frontal operculum have not measured the pars triangularis in

isolation. Furthermore, these studies have been conducted on postmortem specimens that have lacked neurobehavioral information. Therefore, on sagittal volumetric MRI scans, we measured the depths of the convolutions that form the inferior (AHR) and caudal (AAR) extent of the pars triangularis in a group of patients who underwent Wada testing for speech-language lateralization.

As predicted, we found a significant leftward asymmetry of this portion of the pars triangularis. Our data support the findings of others (16–18, 45, 46) who found a leftward asymmetry measuring other portions of anterior speech regions (pars triangularis, pars opercularis) on postmortem brains. Our data also suggest that asymmetries of the pars triangularis may be related to the lateralization of speech-language functions. That is, lateralization of speech-language determined by Wada testing demonstrated a relationship between anatomical asymmetries of the pars triangularis and speech-language dominance. Whereas 9 of the 10 patients with speech-language lateralized to the left hemisphere had a leftward asymmetry of the pars triangularis, the one patient with speech-language lateralized to the right hemisphere had a significant rightward asymmetry of the pars triangularis.

Foundas *et al.* (24) previously measured the planum temporale on volumetric MRI scans in this sample. Therefore, asymmetries of the pars triangularis and planum temporale can be compared in the same individuals, and these asymmetries can be correlated to speech-language lateralization determined by Wada testing. Nine of the 11 patients with speech-language lateralized to the left hemisphere had a leftward asymmetry of the pars triangularis and planum temporale. One patient with speech-language lateralized to the left hemisphere had a rightward asymmetry of the pars triangularis and a leftward asymmetry of the planum temporale. The only patient (nonconsistent right-hander) with speech-language lateralized to the right hemisphere had a rightward asymmetry of the pars triangularis and a rightward asymmetry of the planum temporale. Our data suggest that MRI asymmetries of the pars triangularis and planum temporale may predict speech-language laterality. Although the relationship of hand preference to morphologic asymmetries and laterality of language functions is important to consider, it is beyond the scope of this paper to review this literature and make valid predictions regarding these complex relationships. Furthermore, only one subject in our sample was a nonconsistent right-hander. Therefore, any comment on the relationship of hand preference to morphological asymmetries and speech-language dominance would lack statistical power. Further study of the pars triangularis in larger samples with neurobehavioral correlation of speech-language dominance may confirm these preliminary findings. In addition, it is important to study the relationship of hand preference and other subject variables, such as gender, to asymmetries of the pars triangularis and planum temporale and to relate these variables to lateralized speech-language functions.

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