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Curvature range measurements of the arcuate fasciculus using diffusion tensor tractography☆

Dong Hoon Lee[1], Cheol Pyo Hong[1], Yong Hyun Kwon[2], Yoon Tae Hwang[3], Joong Hwi Kim[4], Ji Won Park[4]

1 *Department of Radiological Science, College of Health Science, Yonsei University, Gangwondo 220-710, Republic of Korea*
2 *Department of Physical Therapy, Yeungnam College of Science & Technology, Daegu 705-703, Republic of Korea*
3 *Department of Physical Therapy, Gangneung Yeongdong College, Gangwondo 210-792, Republic of Korea*
4 *Department of Physical Therapy, College of Medical Science, Catholic University of Daegu, Gyeongsan-si, Gyeongbuk 712-702, Republic of Korea*

Abstract
Because Broca's area and Wernicke's area in the brain are connected by the arcuate fasciculus, understanding the anatomical location and morphometry of the arcuate fasciculus can help in the treatment of patients with aphasia. We measured the horizontal and vertical curvature ranges of the arcuate fasciculus in both hemispheres in 12 healthy subjects using diffusion tensor tractography. In the right hemisphere, the direct curvature range and indirect curvature range values of the arcuate fasciculus horizontal part were 121.13 ± 5.89 and 25.99 ± 3.01 degrees, respectively, and in the left hemisphere, the values were 121.83 ± 5.33 and 27.40 ± 2.96 degrees, respectively. In the right hemisphere, the direct curvature range and indirect curvature range values of the arcuate fasciculus vertical part were 43.97 ± 7.98 and 30.15 ± 3.82 degrees, respectively, and in the left hemisphere, the values were 39.39 ± 4.42 and 24.08 ± 4.34 degrees, respectively. We believe that the measured curvature ranges are important data for localization and quantitative assessment of specific neuronal pathways in patients presenting with arcuate fasciculus abnormalities.

Dong Hoon Lee☆, Studying for doctorate.

Corresponding author: Ji Won Park, Ph.D., P.T., Associate professor, Department of Physical Therapy, College of Medical Science, Catholic University of Daegu, 330 Geumrak 1-ri, Hayang-eup, Gyeongsan-si, Gyeongbuk 712-702, Republic of Korea, mylovept@hanmail.net.

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Key Words
neural regeneration; neuroimaging; clinical practice; diffusion tensor tractography; diffusion tensor imaging; arcuate fasciculus; direct curvature range; indirect curvature range; anatomical location; quantitative information; aphasia; Broca's area; Wernicke's area; arched fiber; grant-supported paper; photographs-containing paper; neuroregeneration

Research Highlights
(1) In this study, the anatomical location and quantitative information on the arcuate fasciculus was provided to help in the treatment of arcuate fasciculus disease. Measurement of curvature range is important for more accurately defining the anatomical characteristics of the arcuate fasciculus.
(2) The degree of curvature of the arcuate fasciculus vertical part in the left hemisphere was less than that in the right hemisphere, and the variation of the arcuate fasciculus angle in the dominant hemisphere was less than that in the other hemisphere.
(3) The detailed arcuate fasciculus curvature information should facilitate the diagnosis and management of patients with aphasia. The results also provide good preliminary arcuate fasciculus curve shape measurements.

Abbreviations
DCR, direct curvature range; ICR, indirect curvature range; ROI, region of interest; FA, fractional anisotropy

INTRODUCTION

Human language function is mediated by two brain areas, Broca's area and Wernicke's area[1-3]. A prominent fiber pathway, the arcuate fasciculus, which connects these two areas, originates in the temporal lobe, curves around the sylvian fissure, and projects to the frontal lobe. The arcuate fasciculus is directly connected to regions of speech production and comprehension. Therefore, interruption of the arcuate fasciculus pathway leads to specific aphasic deficits[1-4]. For this reason, clarification of the anatomical location and quantitative assessment of the arcuate fasciculus are important for clinical neuroscience and for the diagnosis of patients with aphasia.

In the past, many researchers have attempted to determine the location of the arcuate fasciculus in the human brain[1-11]. They have often used invasive methods, such as postmortem brain dissection, encephalotomy, and cortical stimulation during surgery[7-12]. These methods enable the accurate observation of the arcuate fasciculus. However, they have several disadvantages, including being time consuming and requiring painful surgical procedures. Recently, a number of diffusion tensor imaging-based arcuate fasciculus tractography studies have been reported[1-8, 13-28]. Diffusion tensor imaging is a non-invasive neuroimaging technique that allows the visualization and localization of fiber tracts at the subcortical level, and is based on the directional diffusion of water in the white matter[1-8, 19-38]. Most diffusion tensor tractography studies have demonstrated asymmetry in the arcuate fasciculus, with the left arcuate fasciculus larger than the right[13-16, 39-42]. However, these studies are limited in their description of the anatomical localization of the arcuate fasciculus and lack quantitative measurements of the fiber tract[2, 6]. Nevertheless, among these studies, a few of them have reported the anatomy and function of the arcuate fasciculus in greater detail[2, 6]. In 2008, Glasser *et al* [2] reported that the arcuate fasciculus is divided into two segments, with one terminating in the posterior superior temporal gyrus and the other in the middle temporal gyrus. Hong *et al* [6] determined the relative location of the arcuate fasciculus by measuring the distance between the fiber tract and the lateral ventricle using diffusion tensor tractography. However, measurements of the relative location are limited for describing the accurate anatomical location of the arcuate fasciculus because it is a brain association tract composed of arched fibers[1]. Therefore, the arcuate fasciculus is curved, and measurements of the curvature are important for the investigation of arcuate fasciculus anatomy. In this study, we used diffusion tensor tractography to track the arcuate fasciculus connections to the cortical regions. The curvature range of the arcuate fasciculus in the human brain was investigated to provide data on the anatomical location of the fiber tract. This quantitative information should help in the management of patients with arcuate fasciculus abnormalities.

RESULTS

Quantitative analysis of subjects

All 12 healthy subjects were suitable for final analysis.

Curvature range measurements

Table 1 shows the direct curvature range (DCR) and indirect curvature range (ICR) values measured for the arcuate fasciculus horizontal and vertical parts from each subject in the left hemisphere. For the subjects, the maximum and minimum values were 132.88/31.56 and 112.56/22.58 degrees for the DCR/ICR of the arcuate fasciculus horizontal part. For the arcuate fasciculus vertical part, the values were 47.57/32.35 and 32.47/18.12 degrees for the DCR/ICR. Table 2 shows the DCR and ICR values measured for the arcuate fasciculus horizontal and vertical parts from each subject in the right hemisphere. The maximum and minimum values were 130.52/30.11 and 113.96/21.44 degrees for the DCR/ICR of the arcuate fasciculus horizontal part. For the arcuate fasciculus vertical part, the values were 61.48/36.22 and 33.26/22.11 degrees for the DCR/ICR.

Table 1 The arcuate fasciculus curvature range (degree) measurement for each subject in the left hemisphere

Subject	Horizontal part		Vertical part	
	DCR	ICR	DCR	ICR
1	113.63	22.58	40.67	20.56
2	132.88	24.07	47.57	29.23
3	121.76	25.32	44.50	27.45
4	112.56	30.07	36.22	22.57
5	121.96	29.23	41.69	18.12
6	120.96	25.02	32.47	18.29
7	125.31	31.56	33.76	32.35
8	124.26	30.73	42.02	27.01
9	120.96	28.91	36.35	21.04
10	119.51	27.60	41.58	23.90
11	125.00	29.21	37.57	23.96
12	123.32	24.54	38.34	24.57
Mean±SD	121.83±5.33	27.40±2.96	39.39±4.42	24.08±4.34

DCR: Direct curvature range; ICR: indirect curvature range.

Table 2 The arcuate fasciculus curvature range (degree) measurement for each subject in the right hemisphere

Subject	Horizontal part		Vertical part	
	DCR	ICR	DCR	ICR
1	114.55	26.82	46.17	28.71
2	123.96	29.60	61.48	30.85
3	123.21	22.38	46.79	31.22
4	119.52	27.91	43.83	25.77
5	116.19	21.44	54.46	36.22
6	126.21	29.46	40.47	22.11
7	113.96	30.11	33.26	27.80
8	122.47	25.53	47.86	32.08
9	118.09	25.54	39.95	28.74
10	114.70	22.08	37.36	30.96
11	130.19	26.87	38.40	33.69
12	130.52	24.23	37.67	33.69
Mean±SD	121.13±5.89	25.99±3.01	43.97±7.98	30.15±3.82

DCR: Direct curvature range; ICR: indirect curvature range.

The maximum limit of the angles was 180 degrees. In the right hemisphere, the DCR and ICR of the arcuate fasciculus horizontal part were 121.13 ± 5.89 and 25.99 ± 3.01 degrees, respectively. In the left hemisphere, the values were 121.83 ± 5.33 degrees for the DCR and 27.40 ± 2.96 degrees for the ICR. The DCR and ICR values for the arcuate fasciculus vertical part in the right hemisphere were 43.97 ± 7.98 and 30.15 ± 3.82 degrees, respectively. In the left hemisphere, the values were 39.39 ± 4.42 degrees for the DCR and 24.08 ± 4.34 degrees for the ICR. For the arcuate fasciculus horizontal part curvature ranges, there were no significant differences between the DCR and ICR in either hemisphere. However, for the arcuate fasciculus vertical part curvature ranges, there were some differences between the right and left hemispheres. On average, the differences between the two hemispheres for the DCR and ICR for the arcuate fasciculus vertical part were approximately 4 and 6 degrees, respectively.

DISCUSSION

The arcuate fasciculus is the most important pathway in the neural processing of human language. Accurate anatomical localization and quantitative *in vivo* information on the arcuate fasciculus can help treat patients with abnormal language function[10, 43-46]. Neuroscientists have attempted invasive methods in the past to examine the role of the arcuate fasciculus in connecting Broca's and Wernicke's language areas in the dominant hemisphere[7-11, 47-48]. Catani *et al* [47] obtained evidence demonstrating the importance of the arcuate fasciculus in language processing using arcuate fasciculus lesion models. In 1975, Rasmussen *et al* [48] examined the arcuate fasciculus using surgery and Duffau *et al* [8] studied the pathway by performing intraoperative mapping of the subcortical pathways using direct electrical stimulation. However, these methods are invasive and can cause discomfort. In this study, we measured the curvature ranges of the arcuate fasciculus and divided them into two parts–horizontal and vertical–for final analysis. We found that the mediolateral curvature ranges of the arcuate fasciculus vertical part in both hemispheres were different from the arcuate fasciculus horizontal part curvature values, and the degree of curvature of the arcuate fasciculus vertical part in the left hemisphere was less than that in the right hemisphere.

In conclusion, this study aimed to provide information on the generalized anatomical location of the arcuate fasciculus and to generate quantitative information on the fiber tract through an examination of the curvature range of the structure in the normal human brain. We believe that the curvature range measurements provide important data for the management of patients who have arcuate fasciculus disorders. To the best of our knowledge, this is the first study to evaluate and research the curvature values of the arcuate fasciculus in the human brain. Although our results have some limitations with respect to the measurements and region of interest set-up, which are user-dependent operations, they provide good preliminary quantitative arcuate fasciculus curvature measurements and present detailed anatomical localization data for the arcuate fasciculus. Future studies will use a combination of functional MRI and diffusion tensor tractography to provide more accurate localization and morphometric measurements.

SUBJECTS AND METHODS

Design

Neuroimaging, observational study.

Time and setting

All experiments were performed at the Department of Physical Medicine and Rehabilitation, Yeungnam University Hospital, Republic of Korea in June 2008.

Subjects

Twelve healthy subjects, nine males and three females, aged 39 ± 4.13 (range 26–50) years were recruited by volunteers advertising at the Yeungnam University Hospital. They had no previous history of neurological or physical disease. Subjects were restricted to right-handed individuals, and handedness was determined using the Edinburg Handedness Inventory[49]. All subjects understood the purpose of the study and provided written, informed consent prior to participation. The institutional review board of the Yeungnam University Hospital approved the study protocol.

Methods

Diffusion tensor imaging data acquisition

Diffusion tensor imaging data were obtained using a 1.5 T MR scanner (Gyroscan Intera, Philips Healthcare, Best, Netherlands) with a six-channel phased array sensitivity encoding (SENSE) head coil. Each diffusion tensor imaging dataset was acquired with two diffusion-sensitizing gradients based on the single-shot spin echo echo-planar imaging pulse sequence. The imaging parameters were as follows: field of view = 221 mm × 221 mm, repetition time/echo time = 10 726/75 ms, matrix = 128 × 128, slice thickness = 2.3 mm, and SENSE factor = 2. Diffusion weighting was applied along 32 distinct directions with a *b*-value of 1 000 s/mm^2. We obtained 63–67 contiguous transverse slices covering the entire brain parallel to the anterior and posterior commissure lines with no slice gap[6].

The diffusion tensor imaging datasets were transferred to a personal computer running a Windows platform, and image distortion corrections were performed prior to image processing. Image distortion was caused by susceptibility artifacts due to the use of the echo-planar imaging technique and eddy currents due to diffusion gradient changes in diffusion-weighted images. The susceptibility artifacts were reduced using parallel imaging because a reduction of the phase-encoding steps translated directly into a reduced echo train length that reduces phase error in single-shot echo-planar imaging[50-53]. Therefore, we used the SENSE parallel imaging technique with a phased array coil to reduce susceptibility artifacts. The effects of eddy currents and small bulk motion of the head were corrected with 12-mode linear affine registration using each subject's non-diffusion-weighted image (*b*-value = 0 s/mm^2) as a template for all diffusion-weighted images[52-53].

Diffusion tensor imaging data analysis

The diffusion tensor imaging datasets were processed using MedINRIA 1.9.0 software (Asclepios Research Team, Sophia Antipolis, France), which consisted of fiber assignment by the continuous tracking algorithm and calculation of the diffusion tensor values using a deterministic method[54-57]. The six elements of the diffusion tensor were calculated for each voxel and diagonalized. Three eigenvalues and eigenvectors were obtained, and the largest eigenvalue was used as an indicator of fiber orientation. The seed region of interest (ROI) was manually drawn in the posterior parietal portion of the superior longitudinal fascicle, and the target ROI was manually drawn in the posterior temporal lobe using a color-coded fractional anisotropy (FA) map[14, 58-59]. The color-coded FA map showed the directions of the fiber pathways with three colors (red: left-right direction; green: anterior-posterior direction; and blue: superior-inferior direction). The seed ROI was located in the green part, and the target ROI was located in the blue part of the color-coded FA map[6, 58-59]. Tracking was stopped at voxels with FA values that were lower than the threshold or if the angle between two eigenvectors to be connected by the tracking was greater than the threshold. In this study, tracking was terminated when a voxel had an FA value lower than the threshold of 0.2 or a trajectory angle lower than the threshold of 70 degrees.

Curvature range measurements of the arcuate fasciculus

We separately measured the curvature range of the horizontal arcuate fasciculus and the vertical arcuate fasciculus. The arcuate fasciculus curvature range was analyzed in both hemispheres. The ImageJ program (Wayne Rasband, NIH, Bethesda, MD, USA) was used for these analyses.

The arcuate fasciculus horizontal part was examined on transverse images to describe the mediolateral curvature range. We measured two angles, the direct and indirect mediolateral curvatures at the corona radiata level (Figure 1).

The line labeled "1" was parallel to the anterior-posterior direction of the horizontal arcuate fasciculus, and the line labeled "2" was parallel to the arcuate fasciculus, which was directly curved toward the lateral direction. The angles between 1 and 2 determined the DCR. The ICR was defined as the angle between 1 and 3, which is a line connecting the most posterior and most lateral points of the arcuate fasciculus horizontal part.

The arcuate fasciculus vertical part was examined on coronal images to describe the mediolateral curvature range. We applied the same method used for the arcuate fasciculus horizontal part measurements (Figure 1).The DCR was defined by the angle between "1", which is the line parallel to the arcuate fasciculus in the superior-posterior direction, and "2", which is the line along the arcuate fasciculus curvature direction. The ICR was determined by the angle between 1 and 3, which is a line connecting the most superior and most lateral points of the arcuate fasciculus vertical part.

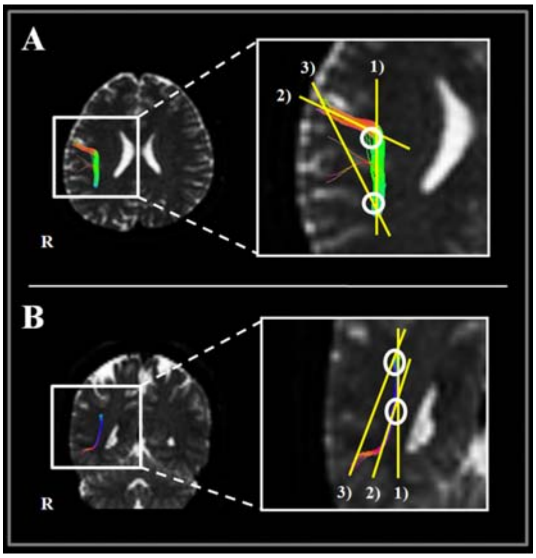

Figure 1 Measurement of the curvature range of the arcuate fasciculus (AF) horizontal and vertical part in the right hemisphere of a healthy human subject.

The tracked AF was superimposed on a transverse image to show the horizontal part (A) and on a coronal image to show the vertical part (B).

The direct curvature range, which is the angle between a line parallel to the anterior-posterior (for horizontal) or superior-inferior (for vertical) direction of the AF on a transverse image (line labeled 1) and a line parallel to the directly curved fibers toward the lateral direction (line labeled 2) was measured horizontally and vertically in both hemispheres.

The indirect curvature range, which is the angle between a line parallel to the anterior-posterior (for horizontal) or superior-inferior (for vertical) direction of the fibers (line labeled 1) and the line connecting the most posterior point and the most lateral point of the fibers (line labeled 3) was also measured horizontally and vertically in both hemispheres.

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Conflicts of interest: None declared.

Ethical approval: This study was approved by the Institutional Review Board of Yeungnam University Hospital in Republic of Korea.

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