Quantitative Analysis of Geometry and Lateral Symmetry of Proximal Middle Cerebral Artery

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Background: The purpose of our work is to quantitatively assess clinically relevant geometric properties of proximal middle cerebral arteries (pMCA), to investigate the degree of their lateral symmetry, and to evaluate whether the pMCA can be modeled by using state-of-the-art deformable image registration of the ipsi- and contralateral hemispheres. *Methods:* Individual pMCA segments were identified, quantified, and statistically evaluated on a set of 55 publicly available magnetic resonance angiography time-of-flight images. Rigid and deformable image registrations were used for geometric alignment of the ipsi- and contralateral hemispheres. Lateral symmetry of relevant geometric properties was evaluated before and after the image registration. *Results:* No significant lateral differences regarding tortuosity and diameters of contralateral M1 segments of pMCA were identified. Regarding the length of M1 segment, 44% of all subjects could be considered laterally symmetrical. Dominant M2 segment was identified in 30% of men and 9% of women in both brain hemispheres. Deformable image registration performed significantly better ($P < .01$) than rigid registration with regard to distances between the ipsi- and the contralateral centerlines of M1 segments (1.5 ± 1.1 mm versus 2.8 ± 1.2 mm respectively) and between the M1 and the anterior cerebral artery (ACA) branching points (1.6 ± 1.4 mm after deformable registration). *Conclusions:* Although natural lateral variation of the length of M1 may not allow for sufficient modeling of the complete pMCA, deformable image registration of the contralateral brain hemisphere to the ipsilateral hemisphere is feasible for localization of ACA-M1 branching point and for modeling $71 \pm 23\%$ of M1 segment. **Key Words:** Human brain—middle cerebral artery—image registration—symmetry—geometry.

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Introduction

With the advent of intra-arterial thrombectomy (IAT) for patients with acute ischemic stroke,[1-3] interest in the anatomical properties of middle cerebral artery (MCA) has increased[4-7] among interventional radiologists. Detailed knowledge of geometrical properties of the MCA is important, especially for planning and performing cerebrovascular or interventional procedures.[3,5,6,8]

The MCA constitutes of 4 main groups of arterial segments, M1-M4: sphenoidal, insular, opercular, and cortical, respectively.[9,10] The morphology of the circle of Willis and the main cerebral arteries in human brain has been studied on dissected cadaveric human brains[11-15] and via digital-image analysis.[16-18] As certain degree of structural and volumetric symmetry exists in the human brain, especially in the bilateral regions such as hippocampus, caudate, and lentiform nuclei,[19,20] quantification of lateral (a)symmetry in human brain may serve as a biomarker for detection of some pathological changes.[21-26]

In a recent work,[6] symmetry of M1 segment of MCA was evaluated via vascular asymmetry coefficient to display the differences between the mean diameters of blood vessel segments. The vascular asymmetry coefficient was expressed as a percentage of the wider vessel with respect to the major diameter.[8]

However, more extensive measurements and quantitative image-based assessments focusing on the geometry and lateral symmetry of the proximal MCA (pMCA) may be useful for planning and performing IAT by providing estimates of the vascular anatomy during the procedure when the occluded vessels are not visible.[27-29]

Therefore, the purpose of our work is to quantitatively assess clinically relevant geometric properties of the pMCA, the degree of their lateral symmetry in both hemispheres, and to investigate whether and to what extent the pMCA can be modeled by using state-of-the-art deformable image registration of both brain hemispheres.

Materials and Methods

Data

Our dataset includes 3T time-of-flight-magnetic resonance angiography (TOF-MRA) scans of 55 healthy adults (M: 21, F: 34) 30.8 ± 10.2 years of age. The MRA-TOF images were originally collected at the Research Imaging Institute, University of Texas Health Science Center at San Antonio, using Siemens TRIO, 3T scanner, and 12-channel head coil using a 3-dimensional (3D), spoiled, gradient echo TOF-MRA sequence with echo time/repetition time/flip angle = 4.4 ms/24.0 ms/18° and 620-µm isotropic resolution. Further, details about the image acquisition can be found in Ref. 16. For the purpose of this project, the data were downloaded from publicly available BraVa database (http://cng.gmu.edu/brava). Individual MRA-TOF images were complemented with manually placed landmarks representing the M1 and M2 segments of the MCA in each brain hemisphere. The identification and manual labeling of M1 and M2 segments was done by 2 experienced interventional radiologists in itkSnap,[30] according to the following classifications:

1. The M1 (horizontal or sphenoidal) segment runs from the bifurcation of the internal carotid artery (ICA) below the anterior perforated substance to the limen insulae. At the limen insulae, the M1 makes a posterosuperior turn (genu) into the insula. The anterior temporal artery is identified as the artery that supplies the anterior temporal pole regardless if it is large and continues into sylvian fissure. All anatomical variations of the early temporal branch originating from M1 were considered M1 branches in this study.
2. The M2 branches are considered those branches that are distally to the main bifurcation at the distal end of the horizontal part of the M1 segment. They extend from the posterosuperior turn (genu) of M1 to the circular gyrus of the insular cortex. The M2 branches were identified on the sagittal images based on this posterior superior course of these arteries over the cortex of the insula. After the identification of the M2 segments, these findings were correlated with transversal and coronal images and, if necessary, with the 3D reconstructions.

Arterial Centerlines and Landmarks

A constant threshold ($I > 200$) was used to separate the arteries from the other brain tissue in the TOF-MRA images. Subsequently, centerlines of these pre-segmented arteries were obtained and annotated (Fig 1). A combination of MeVisLab (http://www.mevislab.de/) and Matlab (http://www.mathworks.com/) was used for processing of the images and visualization of results.

Apart from the pMCA centerlines, 6 landmarks (Fig 2) were identified for assessment of the lateral symmetry of the pMCA segments:

1. the branch point (1) between the anterior cerebral artery (ACA) and the M1 segment,
2. the branch point (10) between the M1 and the M2 segments,
3. landmarks (2 and 3) on individual M2 segments at the distance $d = 4$ mm from the M1 to the M2 branch point.
4. Landmarks (7) and (5) on the centerlines of the ICA and M1, respectively, at the Euclidean distance of 5 mm from the M1 to the ACA branch point (1).

Geometric Properties of pMCA

The following geometric properties are considered valuable for planning and performing cerebrovascular and interventional procedures: