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Asymmetries of the central sulcus in young adults: Effects of gender, age and sulcal pattern

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ABSTRACT

In this study, we clarified the gender and age-related asymmetries of the central sulcus (CS) in early adulthood using a parametric ribbon method. The CS was reconstructed and parameterized automatically from 3D MR images of 112 healthy right-handed subjects. The 3D anatomic morphology of the CS was presented using 5 sulcal parameters, including sulcal depth position-based profile (DPP), average depth (AD), average width (AW), top length (TL) and bottom length (BL). Asymmetry differences in DPPs were found in the medial and lateral part of the CS. In addition, significant gender differences were observed in the medial and middle parts of the right CS DPPs but scattered in the left side. We found leftward asymmetries of TL in males, but rightward asymmetries of AW in females. Males had a greater AW than females in the right hemisphere. Moreover, the females had bilateral longer TL and a longer left BL than did males. We also found significant age-related reductions in bilateral TL and increases in bilateral AW, with males presenting more obvious age-related change than females. There were sexual differences of the CS patterns, in which Type *b* was the most dominant sulcal pattern in males, whereas Type *a* was dominant in females. Three-way ANOVA revealed sexual and asymmetry changes of TL and BL among different CS patterns. Our findings indicate that the lateralization performances of the CS manifest as sexually and regionally different. In addition, it is suggested that males may undergo a faster progress of aging compared to females.

1. Introduction

As an important anatomical landmark of the primary motor and somatic sensory cortex, the central sulcus (CS) plays a prominent role in neurosurgery, neuroradiology and anatomy (Bucholz, 1993; Gonzales-Portillo, 1996; Kamada et al., 1993; Lascano et al., 2014; Meyer et al., 1996; Nii et al., 1996; White et al., 1997a). The CS is one of the most constant, continuous and simplest sulci (Ono et al., 1990). Nevertheless, its shape is still rather complicated and characterized by a high inter-subject variability (Ono et al., 1990). Due to the geometrical complexity of the CS, it is difficult to precisely measure its morphologic parameters from specimens or 2D MR images. Studies of the CS morphology have been greatly facilitated by the recent development of 3D reconstruction and mapping techniques of computational neuroanatomy (Csernansky et al., 2004; Davatzikos and Bryan, 2002; Mangin et al., 2004a).

It is very helpful and important to investigate the 3D morphological features of the CS for exploring the relationship and correspondence between its anatomy and function across human brain (Sastre-Janer et al., 1998; Uematsu et al., 1992) and the potential relationship with the connectivity of the cortex (Van Essen, 1997). Some researchers argued that the lengths of primary sulci could reflect the regional pattern of the cerebral gyrification (Imagawa and Yamadori, 1996; Imai et al., 2011). In addition, the sulcal width is considered as a good neuroimaging indicator of gray mater (GM) atrophy (Kochunov et al., 2005; Liu et al., 2010, 2013a) and decreases in white mater and subcortical volumes (Liu et al., 2013b) in normal aging. Kochunov et al. (2008) suggested that the average sulcal width could be related to regional atrophy of the primary motor and somatic sensory cortex areas. Furthermore, evi-

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dence also indicated that asymmetry in sulcal depth may have a potential relationship with functional asymmetry (Amunts et al., 1996; White et al., 1994, 1997b).

Previous neuroimaging researches indicated that some specific factors (including age, handedness, genetics and training, etc.) might influence the sulcal morphology (Amunts et al., 1997, 2000; Cykowski et al., 2008a; Davatzikos and Bryan, 2002; Le Goualher et al., 2000; Li et al., 2010, 2011; McKay et al., 2013; Rettmann et al., 2006). Moreover, diseases of central nervous system (e.g., schizophrenia, Alzheimer's disease, stutter, autism spectrum and Williams syndrome, etc.) may manifest as abnormalities of the salcal patterns (Auzias et al., 2014; Csernansky et al., 2008; Cykowski et al., 2008b; Fujiwara et al., 2007; Galaburda et al., 1994, 2001; Im et al., 2008; Jackowski and Schultz, 2005; Thompson et al., 1998). Gender differences in sulcal morphologic lateralization are of most considerable interest, especially in the peri-Sylvian and the CS regions given the functional asymmetries of language and handedness (Amunts et al., 2000; Witelson and Kigar, 1988, 1992), respectively. Leftward asymmetries of the Sylvian fissure (SF) length were found in postmortem studies (Galaburda et al., 1978; Ide et al., 1996; Idowu et al., 2014) and in vivo imaging studies (Sowell et al., 2002). The slope of the SF was noted to be greater in the right hemisphere than in left (Blanton et al., 2001; LeMay and Culebras, 1972; Sowell et al., 2002). In addition, Witelson and Kigar (1992) found that SF morphology and hand preference were associated only in men but not women. However, the findings of the CS morphologic studies are still controversial and under dispute. Amunts et al. (2000) noted a significant leftward asymmetry of the CS depth only in males, while Li et al. (2014) observed a reversal asymmetry at the dorsolateral part of the CS in males. Additionally, Cykowski et al. (2008a) found no significant sexual dimorphisms of CS depth. Also, Liu et al. (2010) found that men had a significantly wider CS span than women, but it was not shown in the study of Kochunov et al. (2005).

Age is another hot research focus on sulcal anatomy, and it has also been investigated in several neuroimaging studies. In adults, consistent in most studies are results of age-related decrease in GM volumes along with a concomitant loss in white matter (WM) volumes (Bartzokis et al., 2003; Jernigan et al., 2001; Symonds et al., 1999). Moreover, age-related alterations in sulcal anatomy were prominently reported in central sulcus, Sylvian fissure, superior frontal sulcus and inferior frontal sulcus, etc. (Cykowski et al., 2008a; Im et al., 2006; Kochunov et al., 2005; Li et al., 2011; Liu et al., 2010; Rettmann et al., 2006; Sowell et al., 2002) Some researchers observed significant age-related increases in the CS mean width (Kochunov et al., 2005; Li et al., 2011; Liu et al., 2013b) and decreases in the CS mean depth (Kochunov et al., 2005). However, no significant correlations between age and sulcal depth of the CS were noted in other studies (Cykowski et al., 2008a; Rettmann et al., 2006).

In this study, we measured various morphometric parameters of the CS using high-resolution 3D MR data obtained from 112 young adults. The purpose of this study was to examine the interaction between gender and lateralization in relation to the CS morphology, and their effects on the normal aging progress of the CS in the early adulthood. The CS morphology was investigated via a parametric ribbon method.

2. Material and methods

2.1. Subjects

This study was conducted using data from 112Chinese, healthy, right-handed and age matched volunteers (66 men, 46 women, aged 18–27 years; Table 1). Handedness was determined by the 10-item Edinburgh Inventory (Oldfield, 1971). All subjects were completely asymptomatic, and no abnormal findings were detected by routine MR examinations. Ethics approval was obtained from the ethics committee of Shandong University School of Medicine before the initiation of this study. All subjects gave informed consent according to institutional guidelines.

Table 1
Characteristics of age and EI scores of subjects.

	N	Mean age[a] (years)	SD	Mean EI scores[b]	SD
Male	46	23.2	2.6	96.3	8.9
Female	66	23.4	3.2	97.7	6.8
Total	112	23.3	2.9	97.0	7.9

[a] No significant differences of mean age were found between male and female subgroups by 2-tailed Student's *t*-test ($t = 0.307$, $P = 0.760$).

[b] Subjects with EI scores more than +40 were determined as right-handed. There were no significant differences of mean EI scores between males and females by 2-tailed Student's *t*-test ($t = 0.652$, $P = 0.517$).

2.2. MRI data acquisition

The MR examinations were performed via a GE (General Electric, Milwaukee, USA) 3.0-T MRI Scanner. The magnetic field was kept uniform using Asset Cal sequence. Subsequently, thin sectional MR data were obtained using transverse 3D T1-weighted fast spoiled gradient-echo (FSPGR) sequence (TR/TE = 6.8 ms/2.9 ms; voxel size = 0.47 mm × 0.47 mm × 0.70 mm; FOV = 24.0 cm × 24.0 cm; matrix size = 512 × 512; flip angle = 10°; slice thickness = 1.4 mm; NEX = 2). All images were scanned along a horizontal line through the anterior and posterior commissures.

2.3. Image processing

The raw data was resampled into isotropic voxels (1 mm × 1 mm × 1 mm). Using FLIRT (FMRIB's Linear Image Registration Tool), all images were spatially normalized (Smith et al., 2004; Woolrich et al., 2009), with 9-parameter global spatial normalization, to the Talairach frame (Talairach and Tournoux, 1998) to control the influence of variable brain size. Then, the images were imported into the BrainVisa (BV) database and processed through BV image processing "pipeline" (http://www.brainvisa.info/) (Mangin et al., 2004b).

After non-brain tissue removement and bias correction, brain tissues were segmented into GM, WM and cerebrospinal fluid (CSF) using an intensity based segmentation algorithm (Riviere et al., 2002).

Hemispheric spherical meshes were extracted from segmented GM and WM images with BV image processing pipeline. Subsequently, the central sulci of each subject were reconstructed and extracted automatically with a high identifying accuracy (more than 95%) using an automated sulcal-recognition algorithm (Mangin et al., 2004c; Riviere et al., 2002). Manual identification correction was performed by a skilled neuroanatomist according to an atlas of cerebral sulci (Ono et al., 1990). In order to allow asymmetry comparisons, the right central sulci were mirror-flipped relative to the inter-hemispheric sagittal plane.

2.4. CS parameters measurement

According to the methods of Kochunov et al., sulcal depth is calculated as the distance between the superficial and deep ridges along the sulcal mesh surface (Cykowski et al., 2008a). Sulcal depth was measured at 100 positions along the sulcal long axis in a median-to-lateral direction (Fig. 1), therefore the sulcal depth-position profiles (DPPs) were obtained (Cykowski et al., 2008a; McKay et al., 2013). Then, the average depth (AD) was calculated by