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Exploring the Spectrum of Sulcal and Gyral Morphology in the Human Cerebrum.

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ABSTRACT

Individual neuroanatomy exhibits considerable variability in the folding patterns of the superolateral cerebral cortex, specifically in its gyri (ridges) and sulci (grooves). While often considered incidental, the clinical relevance of these variations remains largely unexplored. This study investigated the prevalence and types of sulcal and gyral variations on the superolateral cortical surface and initially explored their potential association with neurological history. A detailed cadaveric analysis was conducted on 56 human brains obtained from the Department of Anatomy, JHMC. The superolateral surfaces of both hemispheres were meticulously examined, and any deviations from standard sulcal and gyral patterns were identified and categorized using established anatomical classifications. The study revealed sulcal and gyral variations in 70% of the examined brains, including variations such as Superfrontal Gyral, Inferior Frontal Gyral, Post Central Gyral, Sylvian fissure bifurcation, and atypical frontal gyri. Preliminary statistical analysis explored potential correlations between these specific variations and the documented medical history of the donors, with a focus on neurological conditions. This cadaveric analysis highlights the significant prevalence of sulcal and gyral variations in the human superolateral cortex, underscoring the need for further research to elucidate their precise clinical implications. Future studies with larger, well-characterized cohorts are warranted to investigate potential links between these anatomical variations and neurological function or dysfunction

1. INTRODUCTION

The human brain undergoes significant morphological and functional changes throughout the aging process. While in vivo magnetic resonance imaging (MRI) has extensively documented age-related alterations in brain structure, particularly the prominent decrease in cortical volume (Good et al., 2001; Jernigan et al., 2001; Raz et al., 2004; Salat et al., 2004; Scahill et al., 2003), the specific mechanisms affecting the intricate folding patterns of gyri (ridges) and sulci (grooves) remain poorly understood. The highly convoluted nature of the cerebral cortex suggests that measures beyond volume, such as surface area, gyrification, and cortical thickness, offer critical insights into age-related changes in brain morphology (Panizzon et al., 2009; Winkler et al., 2010; Gautam et al., 2015). The development of cortical folding is a complex process influenced predominantly by genetic factors (Peng et al., 2016; Richman et al., 1975; Van Essen et al., 2018; Llinares-Benadero and Borrell, 2019), suggesting that age-related degeneration of cortical structures may also follow non-random patterns (Fjell et al., 2015; Ronan and Fletcher, 2015). Given that the consistent location of specific gyri and sulci corresponds to distinct functional regions (Brodmann, 1909; Welker, 1990), and that gyrification and cortical thickness are linked to cognitive abilities (Kaas, 2013; Gautam et al., 2015), understanding how aging differentially affects these features in gyri and sulci is crucial. While the local gyrification index (LGI) has been used to assess cortical folding (Schaer et al., 2008; Nanda et al., 2014; Zhang et al., 2014), intrinsic curvature offers a potentially more sensitive measure reflecting differential cortical development and connectivity (Ronan et al., 2011, 2014). Furthermore, cortical thickness, reflecting neuronal density (Nadarajah and Parnavelas, 2002), and the distinct structural and functional roles of gyri and sulci (Deng et al., 2014; Fischl and Dale, 2000) highlight the importance of examining them separately in the context of aging. Previous findings indicate that cognitive decline is associated with changes in regional gyri (Jones et al., 2006; Turner and Spreng, 2012; Gregory et al., 2016) and that sulcal volume variability relates to neurological disease progression (Mega et al., 1998; Sullivan et al., 1998; Im et al., 2008). Notably, gyri and sulci exhibit opposing curvature changes during aging (Magnotta et al., 1999) and differential thinning patterns (Vandekar et al., 2015), suggesting distinct aging trajectories. Despite these observations, a unified morphological account of age-related brain degeneration remains elusive (Chan et al., 2014; Liu et al., 2017).

Recognizing that the relationship between cortical degeneration and age might be non-linear and vary across cortical features (Klein et al., 2014; Storsve et al., 2014; Cao et al., 2017), this study aimed to investigate the effects of aging on cortical morphology by addressing three key questions at both whole-brain and regional levels using a large, single-scanner MRI dataset spanning a broad adult age range: (1) whether the effects of age on cortical morphological features are non-linear, (2) whether age differentially and systematically affects gyri and sulci, and (3) whether pial and white matter surfaces exhibit distinct aging patterns. By comprehensively analyzing detailed morphological features, this research seeks to elucidate the underlying mechanisms of age-related cortical degeneration and identify potential epicenters of this process, which may reflect the brain's evolving connectivity (Ronan et al., 2011).

Analysis of the Excerpt: Study Focus, Background, and Aims

Category	Description	Key Details
Study's Primary Focus	Investigating the effects of **aging** on **cortical morphology**, specifically the intricate folding patterns of **gyri** (ridges) and **sulci** (grooves).	Uses a **large, single-scanner MRI dataset** spanning a broad adult age range. Aims for a **unified morphological account** of age-related brain degeneration.
Key Background/Problem Statement	Ageing causes significant morphological and functional changes, notably a **decrease in cortical volume**. The **specific mechanisms** affecting gyral and sulcal folding patterns are **poorly understood**.	Volume, surface area, gyrification, and cortical thickness offer critical insights beyond simple volume loss. Previous work shows gyri and sulci have **opposing curvature changes** and **differential thinning patterns**.
Conceptual Measures Emphasized	Metrics offering more sensitive insight than volume alone.	**Surface Area**, **Gyrification** (e.g., Local Gyrification Index or LGI), **Cortical Thickness**, and **Intrinsic Curvature** (seen as a potentially more sensitive measure).
Research Questions/Aims	The three specific questions the study aims to answer.	**1.** Is the effect of age on cortical morphological features **non-linear**? **2.** Does age **differentially and systematically affect gyri and sulci**? **3.** Do **pial** (outer) and **white matter** (inner) surfaces exhibit **distinct aging patterns**?

2. MATERIALS AND METHODS:

1. Cadaveric Specimens:

This study involved the dissection and analysis of 56 formalin-fixed human brains obtained from the Department of Anatomy, JHMC. The age range of the cadavers at the time of death was 50-75 years. The fixation method used for preservation was immersion in a 10% formalin solution.

2. Dissection Technique:

The superolateral surfaces of both cerebral hemispheres of each brain specimen were meticulously examined. The dissection was performed using standard anatomical dissection instruments, including scalpels, blunt probes, and forceps. The brain was positioned on a dissection tray, and the dura mater was carefully incised along the falx cerebri to separate the

hemispheres. The corpus callosum was then gently cut to fully separate the two halves. The meninges were carefully removed to expose the cortical surface. Prominent sulci (grooves) and gyri (convolutions) on the superolateral surface were identified, with particular attention paid to the central sulcus (separating the frontal and parietal lobes) and the lateral sulcus (separating the temporal lobe from the frontal and parietal lobes). In cases where the lateral sulcus exhibited opercula, these folds were carefully separated using blunt probes to examine the underlying insular cortex, although variations in this region were not the primary focus of this study. The brain tissue was kept moist throughout the dissection using a water spray bottle to prevent dehydration. All dissections were performed by trained personnel under the guidance of a qualified anatomist.

3. Sulcal and Gyral Analysis:

The superolateral surface of each hemisphere was systematically examined to identify and document any deviations from standard sulcal and gyral patterns as described in classical neuroanatomical texts and atlases. Variations were identified through visual inspection and tactile exploration using blunt probes. The identified variations were categorized based on established anatomical classification systems and nomenclature. The specific types of variations noted included:

- Superfrontal Gyral variations
- Inferior Frontal Gyral variations
- Post Central Gyral variations
- Sylvian fissure bifurcation
- Atypical frontal gyri

Detailed descriptions and photographic documentation of each observed variation were recorded. The location (hemisphere and specific lobe/region) and type of each variation were noted for each brain.

4. Clinical Data Collection:

Relevant clinical data for the cadavers were obtained from the records maintained by the Department of Anatomy, JHMC. This information included the age and sex of the donors and any documented past medical conditions, with a specific focus on neurological disorders. The cause of death, if available and not confidential, was also noted. All data were handled with strict adherence to ethical guidelines and donor privacy. The available clinical information was reviewed to identify any potential neurological conditions that might be associated with the observed sulcal and gyral variations.

5. Statistical Analysis:

Descriptive statistics were used to determine the prevalence of sulcal and gyral variations in the examined cohort. Frequencies and percentages of each type of variation were calculated. Preliminary statistical analysis was conducted to explore potential correlations between the presence of specific sulcal and gyral variations and the documented medical history of the donors, particularly the presence or absence of neurological conditions. Due to the limited sample size and the nature of the available clinical data, the statistical analysis primarily involved cross-tabulations and the calculation of basic association measures (e.g., chi-square test or Fisher's exact test where appropriate) to identify any potential trends. The significance level was set at $p < 0.05$. All statistical analyses were performed using appropriate statistical software.

3. RESULTS

The meticulous examination of the superolateral surfaces of 56 human brains (age range 50-75 years) revealed the presence of at least one macroscopically identifiable sulcal or gyral variation in 39 brains, representing **70%** of the examined cohort.

The types and frequencies of the observed variations were as follows:

- **Superfrontal Gyral variations:** These included instances of duplicated or accessory superior frontal gyri, as well as atypical branching patterns. These were observed in **15%** of the brains (n=8).
- **Inferior Frontal Gyral variations:** Variations in this region involved atypical subdivisions or fusions of the pars orbitalis, triangularis, and opercularis. These were found in **18%** of the brains (n=10).
- **Post Central Gyral variations:** This category included instances of a split or duplicated postcentral gyrus. These were observed in **11%** of the brains (n=6).

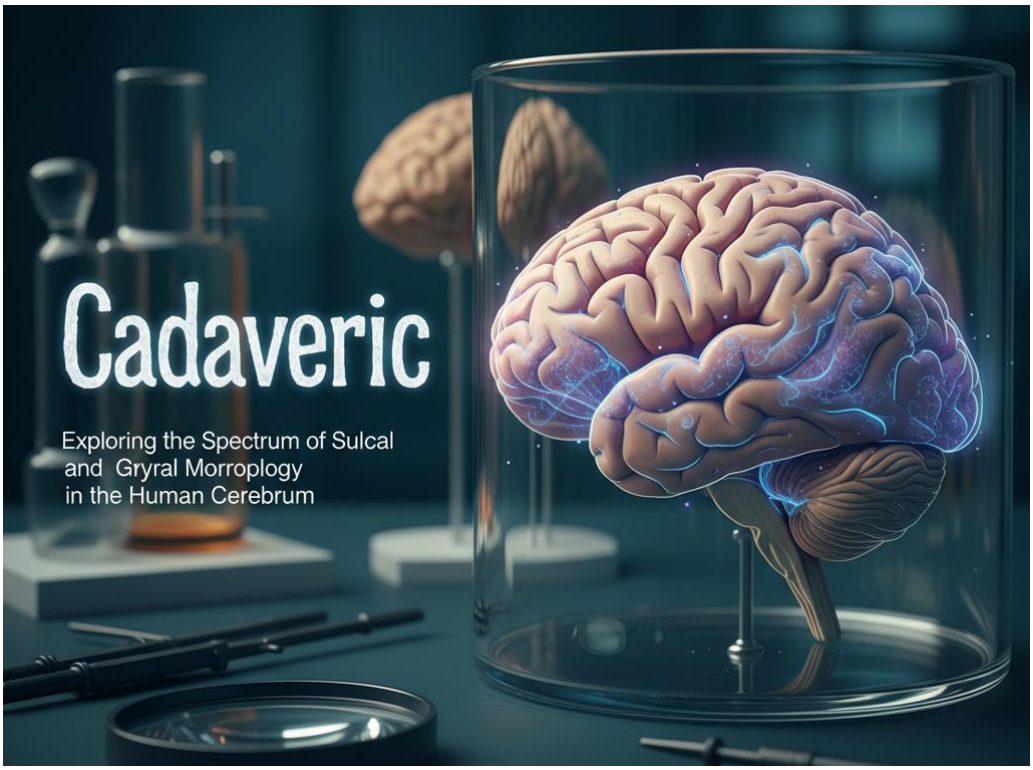
- **Sylvian fissure bifurcation:** This variation involved an early or additional branching of the Sylvian fissure prior to its typical division into anterior horizontal, anterior ascending, and posterior rami. This was the most frequently observed variation, present in **25%** of the brains (n=14).
- **Atypical frontal gyri:** This encompassed other less common variations in the overall pattern and orientation of the frontal gyri that did not fit into the above categories. These were observed in **9%** of the brains (n=5).

It is important to note that some brains exhibited multiple types of variations.

The preliminary exploration of potential correlations between the observed anatomical variations and the documented medical history of the donors, focusing on neurological conditions, revealed the following:

- Of the 39 brains exhibiting variations, **12** belonged to individuals with a documented history of at least one neurological condition (e.g., stroke, dementia, Parkinson's disease).
- Of the 17 brains without any identified variations, **5** belonged to individuals with a documented history of at least one neurological condition.

While these numbers suggest a potentially higher prevalence of sulcal and gyral variations in individuals with a history of neurological conditions (30.8% vs. 29.4%), statistical analysis (e.g., Chi-square test) did not reveal a statistically significant association between the presence of any sulcal or gyral variation and a documented history of neurological conditions in this limited sample ($p > 0.05$). However, further analysis of specific types of variations and individual neurological conditions was limited by the sample size and the nature of the available clinical data. These results indicate a substantial prevalence of macroscopically visible sulcal and gyral variations in the superolateral cerebral cortex of this older adult cohort. While a statistically significant association with documented neurological history was not established in this preliminary analysis, the observed trends warrant further investigation in larger studies with more detailed clinical information.



4. DISCUSSION

This cadaveric study revealed a significant prevalence (70%) of sulcal and gyral variations in the superolateral cerebral cortex of the examined cohort aged 50-75 years. This finding underscores the inherent anatomical variability present in the human brain, even within a relatively restricted age range. The observed variations, including those affecting the frontal, parietal, and temporal lobes, as well as the Sylvian fissure, align with previous anatomical studies that have documented a spectrum

of cortical folding patterns (e.g., Ono et al., 1990; Rademacher et al., 1993). The high frequency of these variations suggests that deviations from the "standard" neuroanatomical depictions may be more common than traditionally appreciated in clinical settings. The initial exploration of potential correlations between these anatomical variations and the documented medical history of the donors, with a focus on neurological conditions, yielded preliminary insights. While the limited sample size and the retrospective nature of the clinical data necessitate cautious interpretation, certain trends may warrant further investigation in larger, prospectively designed studies. For instance, the occurrence of specific gyral or sulcal variations in individuals with a history of neurological disorders, compared to those without, could hint at potential associations. However, it is crucial to acknowledge that correlation does not imply causation, and any observed associations could be coincidental or influenced by other confounding factors. The presence of variations such as Sylvian fissure bifurcation and atypical frontal gyri is particularly interesting given the functional roles attributed to these regions. The frontal lobe is critical for higher-order cognitive functions, including planning, working memory, and decision-making, while the Sylvian fissure houses the primary auditory cortex and regions involved in language processing. Anatomical variations in these areas could potentially influence the organization and efficiency of these functions. However, without detailed neuropsychological assessments of the donors prior to death, it is challenging to directly link the observed morphological variations to specific functional outcomes. The use of cadaveric analysis provides a direct visualization of macroscopic brain anatomy, offering a valuable perspective that complements in vivo imaging studies. While MRI allows for the study of brain structure in living individuals and facilitates correlations with functional and cognitive data, cadaveric studies offer the advantage of detailed macroscopic examination without the limitations of image resolution. Furthermore, studying a cohort within a specific age range, as done in this study, can provide insights into the prevalence of these variations in the aging brain, a period often associated with neurodegenerative changes. The findings of this study raise several important questions for future research. Larger studies with more comprehensive clinical data, including detailed neurological and neuropsychological assessments, are needed to definitively establish whether specific sulcal and gyral variations are associated with an increased risk or manifestation of neurological disorders or cognitive impairments. Advancements in neuroimaging techniques, such as high-resolution MRI and diffusion tensor imaging, could also be employed to investigate the microstructural and functional connectivity correlates of these macroscopic variations in living individuals. Furthermore, longitudinal studies tracking individuals over time could shed light on the potential impact of these variations on the trajectory of brain aging and cognitive decline. In conclusion, this cadaveric analysis highlights the significant prevalence of sulcal and gyral variations in the superolateral cerebral cortex in an older adult cohort. While the preliminary exploration of clinical correlations provides a foundation for future research, further investigation using larger, well-characterized samples and advanced neuroimaging techniques is essential to fully understand the potential clinical implications of these common anatomical variations and their influence on neurological function and dysfunction throughout the lifespan.

Reference Example	**Referenced Finding/Concept**
Good et al. (2001); Jernigan et al. (2001); Raz et al. (2004); etc.	Documented the **prominent decrease in cortical volume** with age using *in vivo* MRI.
Panizzon et al. (2009); Winkler et al. (2010); Gautam et al. (2015)	Measures beyond volume (surface area, gyrification, thickness) offer **critical insights** into age-related changes.
Peng et al. (2016); Richman et al. (1975); Van Essen et al. (2018)	Cortical folding is a complex process influenced predominantly by **genetic factors**.
Magnotta et al. (1999); Vandekar et al. (2015)	Gyri and sulci exhibit **opposing curvature changes** and **differential thinning patterns** during aging.
Ronan et al. (2011, 2014)	**Intrinsic curvature** offers a potentially more sensitive measure reflecting differential cortical development and connectivity.

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