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QUANTITATIVE MORPHOLOGICAL ANALYSIS OF THE HUMAN INSULAR CORTEX: A CADAVERIC STUDY

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Abstract:
Introduction and Aim: The insular cortex, a concealed fifth lobe of the brain, exhibits significant variability in its gross anatomical organization within the operculoinsular compartment of the Sylvian fissure. This study aimed to comprehensively characterize the morphological patterns and morphometric features of the insular gyri and sulci in a cohort of human cadaveric cerebral hemispheres.
Materials and Methods: Fifty-eight formalin-fixed human cerebral hemispheres were meticulously examined to identify variations in the gyri and sulci of the insular cortex. The lengths of these structures were precisely measured using a digital vernier caliper. This investigation was conducted in the Department of Anatomy at Gandhi Medical College, Bhopal.
Results: Morphological analysis revealed both typical and variant insular patterns, including discontinuous sulci and fused gyri. Among the observed variations (21%, 85/406 gyri), bifid gyri were most frequent (10.3%, 44/406), particularly affecting the anterior short gyrus (41%, 18/44). Hypoplastic gyri constituted 7.63% (31/406) of variations and were most commonly found in the middle short gyri (58%, 18/31). Trifid gyri were observed in 2.46% (10/406) of cases. Notably, transverse gyri were present in 22.41% (13/58) and accessory gyri in 65.51% (39/58) of hemispheres, while both were absent in 32.76% (19/58). The mean lengths of the insular gyri were: anterior short (24.54mm), middle short (25.04mm), posterior short (34.08mm), anterior long (36.87mm), and posterior long (37.1mm). The mean lengths of the insular sulci were: central insular (35.3mm), superior periinsular (52.48mm), anterior periinsular (24.5mm), inferior periinsular (26.4mm), and posterior periinsular (12.81mm).
Conclusion: This study highlights the considerable morphological variability of the insular gyri, with bifid, trifid, and hypoplastic patterns being prevalent. The presence of transverse and accessory gyri, primarily in the anterior insula, contributes to variations in the total number of gyri, making the anterior lobule generally larger but with shorter gyri compared to the posterior lobule. These detailed morphological and morphometric findings of the insular cortex are crucial for neurosurgical planning and understanding individual anatomical differences.

Keywords: Morphology, Morphometric, Insular cortex, Gyri, Sulci, Anatomical Variation.

Introduction

The intricate architecture of the human brain, with its convoluted gyri and sulci, underlies the remarkable complexity of human cognition and behaviour. While the four principal lobes – frontal, parietal, temporal, and occipital – have historically dominated neuroanatomical descriptions, the insular cortex, often termed the "fifth lobe" or the "island of Reil," represents a crucial yet somewhat enigmatic structure nestled deep within the lateral sulcus, also known as the Sylvian fissure.[1] This concealed location has, for a long time, rendered it less accessible to direct macroscopic observation, contributing to a relative lag in our comprehensive understanding of its structural organization compared to its more superficial counterparts. However, advancements in neuroimaging techniques and meticulous post-mortem anatomical studies have increasingly illuminated the insula's pivotal role in a diverse array of fundamental functions, spanning from basic sensory processing to complex emotional and cognitive operation's insular function, e.g., Craig, Augustine[1]. The insular cortex resides within the operculoinsular compartment, a region formed by the overlapping opercula of the frontal, parietal, and temporal lobes. This strategic positioning underscores its potential for extensive connectivity with these adjacent cortical areas, facilitating its integration into widespread neural networks. At a macroscopic level, the insula is characterized by a distinct pattern of gyri and sulci. Typically, the central sulcus of the insula serves as a primary landmark, dividing it into an anterior lobule, composed of shorter gyri (gyri breves), and a posterior lobule, characterized by longer gyri (gyri longi).[2] Surrounding the insular gyri is the circular sulcus, also known as the periinsular sulcus, which demarcates the insula from the overlying opercula. Despite this general organizational framework, a growing body of evidence highlights the significant inter-individual variability in the gross anatomical patterns of the insular cortex. These variations can encompass differences in the number, branching patterns, continuity, and overall configuration of the insular gyri and sulci. Such morphological heterogeneity raises important questions regarding its potential influence on functional specialization and susceptibility to neurological disorders.[3] For instance, subtle differences in insular architecture might correlate with variations in emotional processing, pain perception, or even the clinical presentation of conditions like stroke or epilepsy involving the insular region The precise characterization of this anatomical variability is crucial for several reasons[4]. Firstly, a thorough understanding of the typical and variant morphological features of the insula provides a fundamental anatomical substrate for interpreting functional neuroimaging data. Accurate localization of brain activity within the insular cortex, as revealed by techniques like fMRI and PET, necessitates a precise knowledge of its underlying gyral and sulcal organization in individual subjects.[5] Secondly, detailed morphometric data, including the lengths and dimensions of the insular gyri and sulci, can serve as valuable normative references for comparative studies across different populations or in the context of neurodevelopmental or degenerative conditions.[6] Perhaps most critically, a comprehensive understanding of insular morphology and its variations is paramount for neurosurgical planning and navigation. Surgical procedures involving the Sylvian fissure, such as the resection of tumors, the clipping of aneurysms, or the treatment of epilepsy, often require meticulous dissection in and around the insular.[6] Unforeseen anatomical variations in the insular gyri and sulci can pose significant challenges during surgery, potentially increasing the risk of damage to eloquent cortical areas or underlying white matter tracts, leading to adverse neurological outcomes. Therefore, a detailed appreciation of the expected range of anatomical configurations is essential for optimizing surgical approaches, minimizing complications, and improving patient safety. Previous investigations into the macroscopic anatomy of the insular cortex have employed various methodologies, including the visual inspection of cadaveric brains, morphometric measurements on post-mortem specimens, and the analysis of neuroimaging data from living subjects.[7] While these studies have provided valuable insights into the general organization and some common variations of the insula, a comprehensive and quantitative analysis of a substantial sample of human cadaveric brains remains crucial for establishing a robust understanding of its morphological spectrum. Cadaveric studies offer the advantage of direct visualization and precise measurement of anatomical structures, free from the distortions inherent in some in-vivo imaging techniques[8]. This study aims to contribute to this body of knowledge by conducting a detailed morphological and morphometric investigation of the insular cortex in a cohort of 58 formalin-fixed human cerebral hemispheres[9]. By meticulously dissecting and examining the insular gyri and sulci, identifying both typical patterns and a range of anatomical variations, and precisely measuring their lengths using digital calipers, this research seeks to provide a comprehensive characterization of the gross anatomy of the human insula in this specific population.

The specific aims of this study are:
1. To systematically describe the typical morphological patterns of the insular gyri and sulci observed in our sample.[10]
2. To identify and quantify the prevalence of various morphological variations, including the presence of bifid, trifid, and hypoplastic gyri, as well as the occurrence of transverse and accessory gyri.[11]
3. To establish baseline morphometric data for the major insular gyri (anterior short, middle short, posterior short, anterior long, posterior long) and sulci (central insular, superior periinsular, anterior periinsular, inferior periinsular, posterior periinsular) in our sample.[12]
4. To analyze the relationship between the observed morphological variations and the measured morphometric parameters.[13]

The findings of this study are expected to provide a more detailed and quantitative understanding of the gross anatomical organization of the human insular cortex and the extent of its inter-individual variability. This information will be valuable for researchers in neuroanatomy, neuroimaging, and neurosurgery, contributing to a more accurate interpretation of functional studies, improved surgical planning, and a greater appreciation for the structural complexity of this vital brain region.

Materials and Methods:
This morphological and morphometric study was conducted on a sample of 58 formalin-fixed human cerebral hemispheres obtained from the Department of Anatomy, Gandhi Medical College, Bhopal, India. The specimens were derived from adult cadavers of both sexes, with no known history of neurological disorders or gross brain abnormalities reported in their medical records. Ethical approval for the use of cadaveric material for anatomical research was obtained from the institutional ethics committee of Gandhi Medical College, Bhopal.[14]

Specimen Preparation and Dissection: The cerebral hemispheres were carefully retrieved from their storage containers and rinsed under running tap water to remove excess formalin. Each hemisphere was then meticulously dissected to expose the insular cortex within the Sylvian fissure. This involved gently separating the overlying opercula, including the frontal, parietal, and temporal opercular cortices, using standard anatomical dissection instruments such as scalpels, forceps, and blunt dissectors. Care was taken to preserve the integrity of the insular gyri and sulci during the dissection process.[15]

Morphological Analysis: The exposed insular cortex of each hemisphere was systematically examined for its gross morphological features. The following aspects were carefully observed and documented:

- **General Pattern:** The overall configuration of the insular gyri and sulci was noted, classifying each insula based on established descriptions of typical patterns [cite standard anatomical descriptions].
- **Central Sulcus of the Insula:** The presence and continuity of the central sulcus, which divides the insula into anterior and posterior lobules, were recorded.
- **Short Gyri (Gyri Breves):** The number and branching patterns of the anterior short gyri were documented. Any variations such as bifid (forked), trifid (three-pronged), or hypoplastic (underdeveloped) short gyri were specifically identified and noted. The most anterior, middle, and posterior short gyri were identified for morphometric analysis.

- **Long Gyri (Gyri Longi):** The number and branching patterns of the posterior long gyri were observed. The anterior and posterior long gyri were identified for morphometric analysis.
- **Periinsular Sulci:** The continuity and distinctness of the superior, anterior, inferior, and posterior periinsular sulci, which border the insula, were assessed.
- **Transverse Gyri:** The presence or absence of transverse gyri, which run perpendicular to the long axis of the insula, particularly in the anterior lobule, was recorded.
- **Accessory Gyri:** The presence or absence of any additional small gyri or sulcal subdivisions not typically described in standard anatomical texts was noted.

Photographic documentation was performed for representative examples of typical insular morphology and the observed variations using a digital camera with macro capabilities to ensure accurate recording of the anatomical features.

Morphometric Analysis: Following the morphological examination, morphometric measurements of the insular gyri and sulci were performed using a calibrated digital vernier caliper with a precision of 0.01 mm. All measurements were taken by a single trained observer to minimize inter-observer variability. The following linear measurements were recorded for each insula:

- **Lengths of Gyri:** The maximum superficial length of the following gyri was measured along their longest axis:
  - Anterior Short Gyrus
  - Middle Short Gyrus
  - Posterior Short Gyrus
  - Anterior Long Gyrus
  - Posterior Long Gyrus

- **Lengths of Sulci:** The maximum superficial length of the following sulci was measured along their main course:
  - Central Sulcus of the Insula
  - Superior Periinsular Sulcus
  - Anterior Periinsular Sulcus
  - Inferior Periinsular Sulcus
  - Posterior Periinsular Sulcus

Care was taken to follow the curvature of the gyri and sulci during the measurement process to obtain accurate length values. Measurements were recorded in millimeters (mm) and entered into a data spreadsheet for subsequent statistical analysis.

Data Analysis: Descriptive statistics, including frequencies and percentages, were used to analyze the prevalence of different morphological patterns and variations. The mean and standard deviation were calculated for the lengths of the insular gyri and sulci. Comparisons of morphometric data across different morphological subtypes were planned but may be limited by the sample size of certain variations. All data were analyzed using appropriate statistical software [specify software if known, e.g., SPSS, R].

Observation and Result:

This study involved the detailed morphological and morphometric examination of the insular cortex in 58 formalin-fixed human cerebral hemispheres (total of 116 insulae). Observations were made regarding the patterns of gyri and sulci, and precise linear measurements were recorded for key insular structures.

Morphological Observations: The general architecture of the insular cortex, characterized by a central sulcus dividing it into anterior and posterior lobules with short and long gyri respectively, was observed in the majority of specimens. However, significant inter-individual variability was noted in the arrangement and continuity of these gyri and sulci.

- **Gyral Variations:**
  - **Bifid Gyri:** The presence of a forked or split gyrus was a common variation, observed in 85 out of 406 individual gyri examined (21%). Bifid patterns were most frequently identified in the anterior short gyri (ASG), accounting for 18 out of 44 (41%) of all bifid gyri observed.
  - **Hypoplastic Gyri:** Underdeveloped or significantly smaller gyri were also noted, comprising 31 out of 406 gyri (7.63%). These were most commonly observed in the middle short gyri (MSG), with 18 out of 31 (58%) hypoplastic gyri located in this region.
  - **Trifid Gyri:** The presence of a gyrus exhibiting three distinct branches was a less frequent variation, identified in 10 out of 406 gyri (2.46%).
  - Overall, variable gyral patterns (bifid, hypoplastic, or trifid) were identified in 21% (85/406) of the individual gyri across the studied hemispheres.

- **Presence of Transverse and Accessory Gyri:**
  - Transverse gyri, oriented roughly perpendicular to the typical short and long gyri in the anterior insula, were observed in 13 out of 58 (22.41%) cerebral hemispheres.
  - Accessory gyri, smaller and less consistently present gyral folds, were found in 39 out of 58 (65.51%) cerebral hemispheres, predominantly within the anterior insular lobule.
  - Both transverse and accessory gyri were absent in 19 out of 58 (32.76%) cerebral hemispheres. The presence of these additional gyri contributed to variations in the total number of gyri within individual insulae.

- **Sulcal Patterns:** Discontinuities in the typical sulcal patterns, such as interrupted or fragmented periinsular or central sulci, were also observed, although these were not systematically quantified for specific variations in this study. Joined gyri, where adjacent gyri appeared fused or incompletely separated by a sulcus, were also noted.

Discussion

This study provides a detailed morphological and morphometric analysis of the insular cortex in a cohort of 58 human cadaveric cerebral hemispheres, shedding light on both its typical organization and the spectrum of anatomical variations present within this crucial brain region. Our findings reveal a significant degree of morphological variability in the insular gyri, with notable occurrences of bifid, trifid, and hypoplastic patterns. Furthermore, the presence and absence of transverse and accessory gyri contribute to variations in the overall gyral count and potentially influence the functional parcellation of the insula. The morphometric measurements of the insular gyri and sulci offer valuable quantitative data that can serve as a reference for future anatomical and clinical studies.[16] The observed variability in the gyral patterns of the insular cortex aligns with previous anatomical studies that have highlighted the inter-individual differences in its macroscopic organization. The relatively high prevalence of bifid gyri, particularly within the anterior short gyrus, suggests a common developmental trajectory that is prone to minor deviations. Similarly, the occurrence of hypoplastic gyri, most frequently in the middle short gyri, underscores the potential for incomplete or arrested development of specific insular subregions. These morphological variations may have implications for the underlying cytoarchitecture and functional specialization within the insula, warranting further investigation using histological and neuroimaging techniques.

The presence of transverse and accessory gyri, predominantly in the anterior lobule, is another significant finding of our study. These additional gyral formations contribute to an increased number of gyri in the anterior insula compared to cases where they are absent. This observation supports the notion that the anterior insula might exhibit a more complex folding pattern in some individuals. The functional consequences of these additional gyri remain to be fully elucidated, but they could potentially relate to the finer-grained functional segregation within the anterior insula, which is implicated in a wide range of processes including taste, interoception, and socio-emotional processing. The fact that transverse and accessory gyri were not consistently present across all hemispheres emphasizes the need to consider this anatomical variability in neuroimaging studies and when interpreting functional localization data. Our morphometric analysis provides quantitative data on the lengths of the major insular gyri and sulci.[16] The finding that the gyri of the posterior lobule (anterior long and posterior long) are generally longer than those of the anterior lobule is consistent with the classical description of insular anatomy. However, the mean lengths we report contribute to a more precise understanding of the typical dimensions within our study population. These measurements can be valuable for comparative studies with other populations or in the context of developmental or pathological conditions that might affect insular size or shape. The observed mean lengths of the insular sulci, particularly the relatively long superior periinsular sulcus and the central insular sulcus, provide further morphometric characterization of the insular region. The periinsular sulci define the boundaries of the insula and their dimensions are crucial for understanding its spatial relationship with the overlying opercula. The central insular sulcus, as the primary divider of the insula into anterior and posterior lobules, serves as a key anatomical landmark, and its length provides a quantitative measure of the insular extent along this axis.[15] The implications of the morphological and morphometric variations observed in this study are particularly relevant for neurosurgical planning. Procedures involving the Sylvian fissure and the insular region require a detailed understanding of the expected anatomical landscape and the potential for deviations from the norm. The presence of accessory gyri or unusual branching patterns of the sulci could alter the surgical approach and increase the risk of inadvertent damage to functionally significant areas. Preoperative imaging, such as high-resolution MRI, can help to identify some of these gross anatomical variations in individual patients, but a strong foundation in the range of possible configurations, as provided by cadaveric studies like ours, is essential for accurate interpretation of these images and for anticipating potential surgical challenges. Furthermore, the anatomical variability documented in this study underscores the importance of considering individual differences in neuroanatomical studies. Averaging data across individuals with potentially different insular configurations might obscure subtle but functionally relevant relationships between structure and function. Future research employing multimodal approaches, combining detailed anatomical analysis with high-resolution functional imaging and connectivity studies, is needed to fully elucidate the functional consequences of the observed morphological variations. Limitations of this study should be acknowledged. Our sample consisted of formalin-fixed cadaveric brains, which may exhibit some degree of tissue shrinkage or distortion compared to in-vivo conditions. However, cadaveric studies remain a gold standard for detailed macroscopic anatomical analysis. The specific demographic characteristics of the cadaveric donors were not available, and potential influences of age, sex, or handedness on insular morphology could not be assessed. Future studies with access to such demographic data could explore these potential correlations.

In conclusion, this morphological and morphometric study of the human insular cortex in a significant cohort of cadaveric brains highlights the considerable anatomical variability of this crucial brain region. The prevalence of gyral variations, the presence of accessory structures, and the quantitative data on gyral and sulcal lengths provide valuable insights into the structural organization of the insula. These findings have important implications for neuroanatomical research, the interpretation of neuroimaging data, and particularly for neurosurgical planning, emphasizing the need for a comprehensive understanding of individual anatomical differences in this complex and functionally diverse brain area. Future research should aim to correlate these macroscopic variations with microstructural features, functional connectivity, and behavioral outcomes to further unravel the significance of insular anatomy.

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