Section: Anatomy

Original Research Article

A STUDY ON THE DEVELOPMENT OF SULCI AND GYRI IN HUMAN FOETAL CADAVERIC BRAINS AND COMPARING ANATOMICAL WITH RADIOLOGICAL STUDIES

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ABSTRACT

Background: Development of cerebral sulci and gyri is a key event in fetal brain maturation and serves as a reliable indicator of gestational age and neurological integrity. Cortical gyrification follows a precise and sequential pattern, and abnormalities in this process are associated with major neurodevelopmental disorders. Although ultrasonography and fetal MRI are routinely used for prenatal assessment, their ability to accurately determine the timing of sulcal development remains limited. This study aimed to document the chronological development of cerebral sulci and gyri in human fetal brains and to compare anatomical findings with radiological observations. **Materials and Methods:** This study was conducted on 120 cerebral hemispheres from 60 embalmed human fetal cadaveric brains obtained from the Department of Obstetrics and Gynaecology, Victoria General Hospital, Visakhapatnam. Gestational age was estimated using crown–rump length. After fixation in 10% formalin, sulci on the superolateral, medial, and inferior surfaces were examined. The timing of sulcal appearance was recorded and compared with findings from previous anatomical, ultrasonographic, and MRI studies. **Result:** The longitudinal cerebral fissure was present in all specimens. The earliest sulci observed were the lateral and circular insular sulci on the superolateral surface (14 weeks), the callosal and parieto-occipital sulci on the medial surface (13–19 weeks), and the hippocampal sulcus on the inferior surface (14 weeks). Secondary sulci appeared between 28 and 30 weeks. By 33 weeks of gestation, all primary sulci were fully formed. Anatomical observations demonstrated sulcal development approximately 2–4 weeks earlier than that reported by ultrasonographic and MRI studies. **Conclusion:** Cerebral sulcal development follows a predictable sequence closely related to gestational age. Anatomical studies provide a more accurate depiction of sulcal maturation than current prenatal imaging techniques and serve as an essential reference for prenatal neurodevelopmental assessment.

INTRODUCTION

The human nervous system is the most complex product of biological evolution. The constantly changing patterns of activity of its billions of interactive units represent the fundamental physical basis of every aspect of human behaviour and experience. The brain (encephalon) lies within the cranium. It receives information from and controls various activities of the Human body.[1]
The adult human cerebral cortex is highly convoluted, variable in shape across regions and individuals, and asymmetric in both structure and function.[2] The surface of the developing fetal brain undergoes significant morphological changes throughout its development. The formation of cortical convolutions is an important aspect of normal cerebral development.[3] Gyration is a phenomenon occurring late during fetal development and can be observed by the second month of intrauterine life. It goes on to the end of the pregnancy and even later, after birth. The primary sulci appear as shallow grooves on the surface of the brain that become progressively more deeply infolded and develop side branches, designated secondary sulci. Gyration proceeds with the formation of other side branches of the secondary sulci, referred to as tertiary sulci.[4,5] At term birth, although the brain is only one-third of

adult volume,[6] the major sulci and gyri present in the adult are already established.[7]
Understanding the relationship between cortical folding in infants and adults is important for establishing a baseline for normal cortical maturation. The timing of the appearance of these different types of sulci is so precise that neuropathologists consider gyration to be a reliable estimate of gestational age and consequently a good marker of fetal brain maturation. The study of their embryological appearance can be of great assistance, not only for a better general understanding of anatomy but also in dealing with practical gestational, neuroradiological, and micro neurosurgical issues.
The development of cerebral sulci and gyri is a fundamental aspect of foetal brain maturation. The precise timing and pattern of these developments are critical for normal neurodevelopment and can serve as indicators of gestational age and potential neurological disorders. Anomalies in sulcal development, such as the absence (agyria) or reduced number (pachygyria) of gyri, can be indicative of conditions like lissencephaly, which are associated with significant developmental delays and neurological impairments.[8]
This study aims to provide a comprehensive analysis of the development of sulci and gyri in human fetal cadaveric brains, examining the chronological appearance and maturation of these structures. By comparing anatomical findings with radiological imaging results, we seek to identify potential discrepancies and assess the accuracy and reliability of imaging techniques in evaluating fetal brain development. The findings from this study will contribute to a deeper understanding of fetal neurodevelopment and may inform clinical practices related to prenatal diagnosis and management of neurological conditions.

MATERIALS AND METHODS

The study was done on 120 hemispheres of 60 fetal cadaveric brains. The dead fetuses were obtained from the Department of Obstetrics and Gynecology, Victoria General Hospital, Visakhapatnam. Among the 60 fetuses, 28 were female and 32 were male. They were dissected after proper embalming. The specimens obtained are fixed in 10% formalin.
Method
Preservation of foetus: The fetuses were injected with 10% formalin through the umbilical vessel and the abdominal cavity. 10% formalin is injected directly into the cranial cavity through the anterior fontanelle. After injecting formalin, the embalmed fetuses are kept in formalin tanks containing 10% formalin solution for a minimum period of one month. Then they were thoroughly washed with water and their Age, Sex, Weight, Crown-rump length (CRL), and Bi biparietal diameter (BPD) were recorded.
The removed brains were fixed in 10% formalin solution for at least 1 month, and the weights were taken with the arachnoid and pia mater in situ. The weight of the whole brain, including the cerebellum, is taken. The foetuses were weighed with the help of a digital weighing machine, and crown-rump lengths were measured with the help of a measuring tape. This is to calculate the fetal gestational age according to the crown-rump length as per the description of Langman's Human Embryology.
Removal of brain: After removing the skull cap, the dura mater was removed in four quadrants. The falx cerebri was detached from its attachments to the crista galli and pulled posteriorly between the hemispheres. The olfactory bulbs were separated from the floor and are divided close to the optic foramina. The internal carotid artery and infundibulum are cut. The head was turned to one side, and the posterior part of the upper hemisphere was raised with fingers from the tentorium. Then, the tentorium cerebelli was divided along its attachment to the petrous temporal bone, avoiding injury to the cerebellum beneath it. Then the brain was allowed to fall well backwards to draw the brain stem away from the anterior wall of the posterior cranial fossa. Pons was pressed further posteriorly, and the medulla oblongata was cut near the foramen magnum. Vertebral arteries were also cut at the same point. The brain was withdrawn from the cranium. After removing the brains from the cranium, they were stored in containers filled with 10% formalin. For a detailed study, brains were washed in running water, and then the meninges were completely removed from the brain along with the vessels. This will expose the sulci and gyri very clearly for detailed study.

RESULTS

We observed that the longitudinal cerebral fissure was always already formed in all the fetal brains
Study of Sulci on Superolateral Surface [Table 1 & Figure 1]
Central sulcus: It appeared at 19th week of IUL. The average length of the sulcus is 4.4 cm. The average depth of sulcus at the upper end is 0.7 cm.
Lateral sulcus: In the present work, it appeared as lateral cerebral fossa around 14th week. Later, it deepened to form the lateral cerebral fissure and the insula, which is present at its floor. In full-term fetal brains, insula is completely covered by the opercula. The average length is 7.5cm and average depth is 0.5 cm.
Precentral sulcus: It appeared by 28th week of IUL. Its average length is 4.2 cm, and its average depth is 0.6 cm.
Postcentral sulcus: It appeared at 28th week of IUL. Its average length is 4.2 cm, and its average depth is 0.6 cm
Superior frontal sulcus: In the present study, it appeared at 28th week of IUL. In fetal brains, the

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average length is 5.9 cm and the average depth is 0.7 cm.

Inferior frontal sulcus: It appeared at 30 weeks of IUL. In fetal brains its average length is 2.9 cm and its average depth is 0.6 cm.

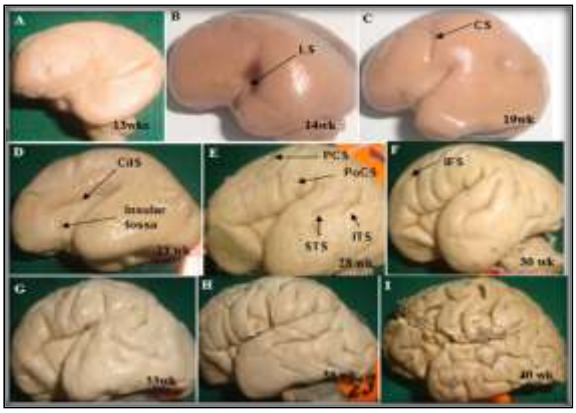

Figure 1: Development of sulci on the superolateral surface of the fetal brain. (A) 13 weeks and (B) 14 weeks of intrauterine life, with the arrow indicating the initial appearance of the lateral sulcus (LS). (C) 19 weeks, showing the initial appearance of the central sulcus (CS). (D) 23 weeks, demonstrating the insular fossa surrounded by the circular insular sulcus (CilS). (E) 28 weeks, showing the precentral sulcus (PCS), postcentral sulcus (PoCS), superior temporal sulcus (STS), and inferior temporal sulcus (ITS). (F) 30 weeks, showing the inferior frontal sulcus (IFS). (G) 33 weeks, (H) 38 weeks, and (I) 40 weeks, demonstrating progressive maturation and deepening of sulci.

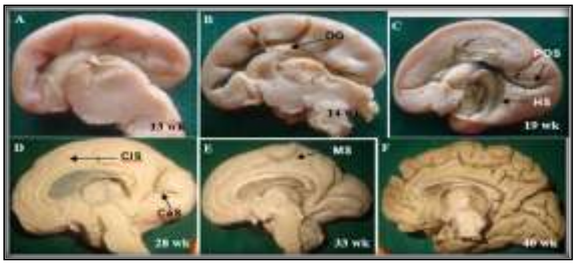

Figure 2: Development of sulci on the medial surface of the fetal brain. (A) 13 weeks and (B) 14 weeks of intrauterine life, with the arrow indicating the initial appearance of the dentate gyrus (DG). (C) 19 weeks, showing the parieto-occipital sulcus (POS) and hippocampal sulcus (HS). (D) 28 weeks, demonstrating the cingulate sulcus (CiS) and calcarine sulcus (CaS). (E) 33 weeks, showing the marginal sulcus (MS). (F) 40 weeks, illustrating further maturation and deepening of medial surface sulci.

Superior temporal sulcus: It appeared at 23rd week of IUL. Its average length in the fetal brain is 6.4 cm, and its average depth is 0.7 cm.

Inferior temporal sulcus: It appeared at 28th week of IUL. In fetal brains, its average length is 3.8 cm and its average depth is 0.6 cm.

Intra-Parietal sulcus: It appeared at 28th week of IUL. In fetal brains its average length is 1.9 cm and its average depth is 0.4 cm.

Sulci on the medial surface of cerebral hemispheres [Table 1 & Figure 2]

Cingulate sulcus: It appeared at 28th week of IUL. The average length of the fetal brain is 5.9 cm, and its average depth is 0.6 cm.

Parieto-occipital Sulcus: It appeared at 19th week of IUL. The average length in the fetal brains is 3.2 cm and its average depth is 0.7 cm.

Calcarine Sulcus: It appeared at 23rd week of IUL. The average length in the fetal brains is 2.9 cm and its average depth is 0.5 cm.

Sulci on the Inferior surface of cerebral hemisphere [Table 1 & Figure 3]

Olfactory sulcus: It appeared at 23rd week of IUL. Its average length in fetal brains is 1.6 cm and the average depth is 0.4 cm.

Orbital sulcus: It appeared at 33rd week of IUL.

Collateral Sulcus: It appeared at 28th week of IUL. The average length in the fetal brains is 4.3 cm and its average depth is 0.6 cm.

Rhinal sulcus: It appeared at 23rd week of IUL. It is 1.6 cm long and 0.3 cm deep in fetal brains.

Occipito-temporal sulcus: It the present study it appeared in 28th week of IUL (Photograph -16). In fetuses, its average length is 4.7 cm and average depth is 0.7 cm.

Insula /Island of Reil: Circular insular sulcus appeared at 28th week of IUL and central insular sulcus appeared at 33rd week of IUL.

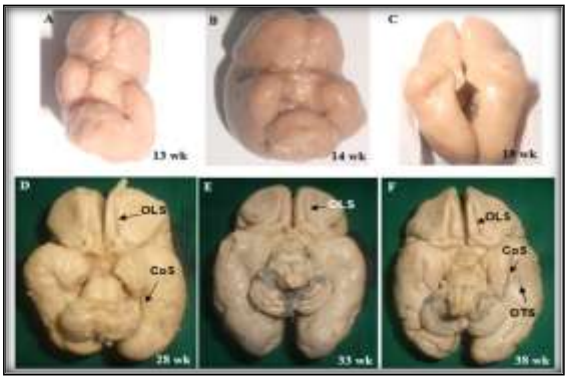

Figure 3: Development of sulci on the inferior surface of the fetal brain. (A) 13 weeks and (B) 14 weeks of intrauterine life showing a relatively smooth inferior surface. (C) 19 weeks demonstrating the initial appearance of sulcal grooves. (D) 28 weeks showing clearly identifiable olfactory sulcus (OLS) and collateral sulcus (CoS). (E) 33 weeks, with the arrow indicating the olfactory sulcus (OLS). (F) 38 weeks showing well-defined olfactory sulcus (OLS), collateral sulcus (CoS), and occipito-temporal sulcus (OTS).

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Table 1: Comparison of the development of sulci with Anatomical studies

Sulcus	Dorowini-ziz & Dolman 1977	Chi et al 1977	Larroche 1981	Nishikuni 2006	Present study
Superolateral surface					
Lateral sulcus		14		17	14
Circular insular sulcus	-	18	-	17	14
Central insular sulcus	-	-	-	29±2	33
Central sulcus	24	20	20	21	19
Precentral sulcus	26	24	28	26±3	28
Superior frontal sulcus	26	25	-	25±2	28
Inferior frontal sulcus	-	28	-	30±3	30
Post central sulcus	26	25	-	26±3	28
Intraparietal sulcus	-	26	-	29±2	28
Transverse occipital sulcus	-	-	-	30±3	33
Lunate sulcus	-	-	-	24±2	33
Superior temporal sulcus	28	23	28	26±3	23
Inferior temporal sulcus	-	30	-	31±3	28
Medial surface					
Callosal sulcus	-	14	18	12	13
Cingulate sulcus	24	18	-	19	28
Marginal sulcus	-	-	-	30±3	33
Paracentral sulcus	-	-	-	30±3	37
Parolfactory sulcus	-	-	-	29±2	37
Sub parietal sulcus	-	-	-	30±3	33
Calcarine sulcus	18	16	22	17	23
Parieto occipital sulcus	18	16	22	17	19
Inferior surface					
Olfactory sulcus	-	16	-	17	23
Orbital sulcus	-	-	-	22	33
Hippocampal sulcus	-	10	-	15	14
Rhinal sulcus	-	-	-	25±2	23
Collateral sulcus	-	23	-	24±2	28
Occipito temporal sulcus	-	30	-	30±3	28

Table 2: Comparison of the development of sulci with ultrasonographic studies

Sulcus	Monteagudo & Timor-Tritsch, 1997	Bernard et al, 1998	Toi et al, 2004	Cohen-sacher et al 2006	Present study
Superolateral surface					
Lateral sulcus	18	-	17	18	14
Circular insular sulcus	-	-	-	-	14
Central insular sulcus	-	-	-	32	33
Central sulcus	-	-	-	28	19
Precentral sulcus	-	-	-	30	28
Superior frontal sulcus	-	-	-	30	28
Inferior frontal sulcus	-	-	-	30	30
Post central sulcus	-	-	-	30	28
Intraparietal sulcus	-	-	-	-	28
Transverse occipital sulcus	-	-	-	-	33
Lunate sulcus	-	26-28	-	-	33
Superior temporal sulcus	-	-	-	30	23
Inferior temporal sulcus	-	-	-	30	28
Medial surface					
Callosal sulcus	14	19	-	18	13
Cingulate sulcus	26	22-24	23	24	28
Marginal sulcus	-	30	-	30	33
Paracentral sulcus	-	-	-	-	37
Parolfactory sulcus	-	-	-	-	37
Sub parietal sulcus	-	-	-	-	33
Calcarine sulcus	18	23	19	22	23
Parieto occipital sulcus	18	23	19	20	19
Inferior surface					
Olfactory sulcus	-	-	-	30	23
Orbital sulcus	-	-	-	-	33
Hippocampal sulcus	-	-	-	18	14
Rhinal sulcus	-	-	-	-	23
Collateral sulcus	-	23-25	-	-	28
Occipito temporal sulcus	-	-	-	-	28

Table 3: Comparison of the development of sulci with MRI studies

Sulcus	Levine & Barnes 1999	Lan et al, 2000	Ruoss et al, 2001	Garel et al, 2001	Present study
Superolateral surface					
Lateral sulcus	16-17	15	-	-	14
Circular insular sulcus	18-19	-	-	33	14
Central insular sulcus	32-33	-	-	-	33
Central sulcus	26-27	24-26	24.5-32	24-25	19
Precentral sulcus	26-27	27-29	-	-	28
Superior frontal sulcus	-	-	-	26	28
Inferior frontal sulcus	30-31	-	-	26	30
Post central sulcus	28-29	27-29	-	26	28
Intraparietal sulcus	-	24-26	-	27	28
Transverse occipital sulcus	-	-		-	33
Lunate sulcus	-	-	-	-	33
Superior temporal sulcus	28-29	24-26	-	26	23
Inferior temporal sulcus	30-31	-	-	30	28
Medial surface					
Callosal sulcus	-	-	32-40	22-23	13
Cingulated sulcus	24-25	-	28-33	24-25	28
Marginal sulcus	-	-	-	22-23	33
Paracentral sulcus	-	-	-	-	37
Parolfactory sulcus	-	-	-	-	37
Sub parietal sulcus	-	-	-	-	33
Calcarine sulcus	18-19	-	29-38	22-23	23
Parieto occipital sulcus	18-19	-	30-33	22-23	19
Inferior surface					
Olfactory sulcus	-	-	-	-	23
Orbital sulcus	-	-	-	-	33
Hippocampal sulcus	-	-	-	22-23	14
Rhinal sulcus	-	-	-	-	23
Collateral sulcus	-	-	-	24-25	28
Occipito temporal sulcus	-	-	-	-	28

DISCUSSION

Anatomical studies [Table 1]

The present study provides a comprehensive comparison of sulcal development across gestational weeks by analyzing our findings alongside those of established anatomical studies by Dorowini-Ziz & Dolman (1977),[9] Chi et al. (1977),[7] Larroche (1981),[10] and Nishikuni et al. (2006).[11] The results reveal both consistent patterns and noteworthy variations in the developmental timeline of cerebral sulci [Table 1].

A key observation is the early appearance of primary sulci, particularly the lateral sulcus, which was consistently detected by 14–17 weeks across studies, including the present one. This aligns with the recognized sequence of cortical folding, where primary sulci such as the central and lateral sulci are among the first to form due to their association with major functional cortical areas. The central sulcus appeared slightly earlier in our study (19 weeks) compared to Dorowini-Ziz & Dolman (24 weeks), reflecting possible population differences or improved imaging and histological techniques in recent times.

In contrast, secondary and tertiary sulci, such as the marginal sulcus, paracentral sulcus, and parolfactory sulcus, appeared much later, often around 30–37 weeks in our study. These later-developing sulci are typically associated with the expansion of association cortices, supporting the view that gyrification follows a hierarchical and functionally driven maturation process.

The insular region demonstrated particular variability. While the circular insular sulcus was visible by 14–18 weeks, the central insular sulcus was not reported in earlier literature but was clearly identified in our study by 33 weeks. This discrepancy may be due to its deep location and subtle appearance, which may have limited its detection in earlier gross anatomical studies.

On the medial surface, sulci such as the cingulate and callosal sulci were identified between 12–28 weeks. Notably, the cingulate sulcus showed a wider range of appearance across studies, likely reflecting inter-individual variability in its extent and branching pattern. The late development of the sub parietal and parolfactory sulci supports the idea that the medial cortex undergoes more prolonged maturation.

Sulci of the inferior surface, including the olfactory, rhinal, and collateral sulci, also showed a delayed pattern of emergence, consistent with their location in limbic and ventral temporal regions. The orbital sulcus, identified at 33 weeks in the present study, was not consistently reported in prior studies, suggesting an under-recognition of sulci in the basal frontal cortex in earlier anatomical investigations.

Importantly, the present study shows slightly later appearance of several sulci compared to historical data. This may reflect methodological differences, including improved fetal brain imaging, refined histological sectioning, and larger sample sizes. It may also point to population-specific variations in sulcal maturation, underscoring the need for regional developmental reference data.

Overall, our findings reinforce the sequential and predictable nature of sulcal development, beginning with primary sulci and followed by progressively more complex folding. The later appearance of higher-order sulci may correlate with the maturation of associative and integrative cortical networks. These insights are crucial for gestational age estimation, prenatal neurodevelopmental assessment, and identification of cortical dysgenesis in utero.

Comparing with ultrasonographic studies [Table 2]

The comparison of sulcal development observed in the present study with previous ultrasonographic investigations done by Monteagudo & Timor-Tritsch, 1997,[12] Bernard et al,[13] Toi et al, 2004,[14] Cohen-Sacher et al 2006,[15] reveals both concordance and notable differences in the timing of sulcus appearance during fetal neurodevelopment.

The lateral sulcus is one of the most consistently visualized sulci across studies, appearing as early as 14 weeks in our anatomical series and 17–18 weeks in sonographic studies. This supports its role as a primary sulcus and a key developmental marker in prenatal neuroimaging.

While many sulci were not reported or were invisible in early ultrasonography, particularly the circular insular, central insular, and orbital sulci, they were well defined in the present anatomical analysis. For instance, the central insular sulcus was detected at 33 weeks in both the present and Cohen-Sacher et al.'s study,[15] but not in earlier ultrasound literature, suggesting that deep sulci are challenging to detect with conventional sonography, especially prior to the third trimester.

Sulci such as the central, precentral, and postcentral sulci appeared much earlier in our anatomical study (19–28 weeks) compared to the 28–30 weeks typically reported by Cohen-Sacher et al. The superior and inferior frontal sulci, also visualized around 30 weeks in ultrasonographic studies, were identifiable by 28–30 weeks anatomically. This reinforces the view that ultrasound tends to detect sulcal development later than direct anatomical or MRI-based observation, likely due to its lower spatial resolution and operator-dependent variability.

The medial surface sulci, including the cingulate and callosal sulci, showed more consistent findings. The cingulate sulcus was noted between 22–26 weeks in ultrasound studies and at 28 weeks in the present study. However, tertiary medial sulci such as the paracentral, parolfactory, and sub parietal sulci were only recognized in our anatomical dataset and were not reported in any ultrasonographic study, indicating their limited visibility or lack of emphasis in prenatal ultrasound protocols.

Sulci of the inferior surface, including the olfactory, rhinal, and collateral sulci, were again more consistently detected in the present study than in ultrasound. The olfactory sulcus appeared at 23 weeks anatomically and only at 30 weeks in sonography (Cohen-Sacher et al.). The hippocampal sulcus, detected as early as 14–18 weeks in our study and in some sonographic reports, underscores its early and stable development despite its deep location.

Overall, the present anatomical findings indicate an earlier and more complete visualization of sulcal development than ultrasonographic studies. This discrepancy highlights the need for enhanced imaging protocols or integration with fetal MRI to improve prenatal neurodevelopmental assessment. Moreover, the variability across studies emphasizes the importance of establishing standardized sonographic criteria and gestational timelines for evaluating cortical maturation.

Comparing with MRI studies [Table 3]

The comparative evaluation of sulcal development as observed in the present anatomical study and previously published fetal MRI studies by Levine & Barnes (1999),[16] Lan et al. (2000),[17] Ruoss et al. (2001),[18] and Garel et al. (2001).[19] Overall, our anatomical findings demonstrate a high level of concordance with MRI-based observations for primary and secondary sulci, while offering earlier and more consistent identification of tertiary and deep sulci, particularly on the medial and inferior surfaces.

1. Concordance for Primary Sulci

The lateral sulcus, one of the earliest and most consistently visualized sulci in fetal neuroimaging, was identified at 14 weeks in the present study. This aligns well with MRI observations by Lan et al. (15 weeks) and Levine & Barnes (16–17 weeks), affirming its role as a key early developmental marker. Similarly, the central sulcus appeared at 19 weeks anatomically, earlier than the MRI-based estimates (24–27 weeks), suggesting that anatomical methods may detect sulcal landmarks before they are readily apparent on imaging.

2. Precentral and Postcentral Sulci: Near Parity Between Modalities

The precentral and postcentral sulci, typically observed between 26–29 weeks in MRI studies, were detected at 28 weeks in the present study. This parity suggests that once sulci become prominent enough structurally, they can be reliably identified through both imaging and dissection. The consistent detection of these motor-related sulci across modalities underscores their importance in assessing fetal brain maturation.

3. Delayed or Inconsistent Reporting of Deep and Tertiary Sulci in MRI

Several sulci identified in the present study—especially those located deep in the cortex or on medial/inferior surfaces—were not consistently reported in earlier MRI studies. Notable examples include:

- Paracentral and parolfactory sulci (appearing at 37 weeks in our study) were absent from MRI literature.
- The marginal sulcus, a component of the cingulate system, was observed at 33 weeks in our

study but was largely unreported or vaguely documented in imaging studies.
- The circular insular sulcus, which encircles the insular cortex, was identified as early as 14 weeks anatomically, yet only reported at 18–19 weeks by Levine & Barnes and at 33 weeks by Garel et al., suggesting under-detection in imaging due to its location and depth.

4. Medial Surface Sulci: Enhanced Anatomical Visibility

MRI studies offered only limited data on sulci located on the medial cerebral wall, such as the callosal, sub parietal, and paracentral sulci. In contrast, these sulci were readily identifiable in the present anatomical study, often well before their first appearance in imaging. For instance:
- The callosal sulcus appeared at 13 weeks anatomically, while MRI studies reported it between 22–40 weeks (Ruoss et al.).
- The cingulate sulcus, which develops along the midline limbic area, was noted at 28 weeks, consistent with MRI findings (24–33 weeks).

5. Inferior Surface Sulci: Poor Representation in MRI Literature

Sulci on the inferior (basal) surface of the brain—such as the olfactory, rhinal, orbital, and occipito-temporal sulci—were either completely unreported or inconsistently described in MRI studies. These were, however, clearly observed and dated in the present study:
- Olfactory sulcus at 23 weeks
- Orbital sulcus at 33 weeks
- Collateral and occipito-temporal sulci at 28 weeks

This discrepancy highlights an important limitation of fetal MRI: difficulty in visualizing the ventral brain surface due to fetal position, motion, and reduced spatial resolution in earlier-generation scanners.

CONCLUSION

The present study provides a detailed and systematic account of the chronological development of cerebral sulci and gyri in human fetal brains, based on direct anatomical examination and comparative analysis with ultrasonographic and MRI-based studies. The findings reaffirm that cortical folding follows a highly ordered, sequential, and functionally driven pattern. Initially, the cerebral surface is smooth; transient furrows form, leading to the emergence of permanent sulci, which begin as small points or grooves and gradually evolve into deeper depressions. By the 33rd week of gestation, all primary sulci are fully formed, and secondary sulci begin to develop.

A major strength of this study is the demonstration that anatomical examination allows earlier, clearer, and more comprehensive identification of sulcal landmarks compared to imaging modalities. Primary sulci such as the lateral and central sulci were consistently identified earlier in the present anatomical series than in both ultrasound and MRI studies. Moreover, several deep, medial, and inferior surface sulci—including the paracentral, parolfactory, marginal, orbital, and occipito-temporal sulci—were reliably documented in this study but were inconsistently reported or entirely absent in prior imaging literature. These discrepancies highlight inherent limitations of prenatal imaging, particularly in visualizing deeply located or ventrally placed cortical structures.

Comparison with ultrasonographic studies revealed that sonography generally detects sulcal development at later gestational ages, likely due to lower spatial resolution, operator dependency, and limited visualization of complex cortical regions. While fetal MRI showed better concordance with anatomical findings for primary and some secondary sulci, it still underrepresented tertiary sulci and those on the medial and inferior surfaces. This underscores the continued importance of anatomical studies as the gold standard for validating and refining prenatal neuroimaging interpretations.

Overall, the study enhances existing knowledge of fetal cortical maturation by providing precise gestational timelines and highlighting inter-study variability that may arise from methodological differences or population-specific factors. The findings have significant clinical implications, offering valuable reference data for gestational age estimation, improving the interpretation of prenatal imaging, and aiding in the early detection of abnormalities of cortical development. Integrating detailed anatomical data with advanced imaging techniques may ultimately improve the accuracy of prenatal diagnosis and contribute to better clinical management of fetal neurological conditions.

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