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Forensic Anthropological Study on the Estimation of Age Using Skull Vault Suture Fusion: A Preliminary Study

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Abstract

Age estimation of deceased individuals is a critical aspect of forensic anthropology, especially for the identification of unknown cadavers. Although various countries have established reliable age estimation methods based on cranial suture fusion, these findings often do not directly translate to the Sri Lankan population due to unique population characteristics and forensic needs. This study aimed to estimate age at death through the assessment of skull vault suture fusion patterns and to analyze how fusion of different sutures correlates with advancing age in a Sri Lankan cohort. Conducted at Colombo South Teaching Hospital, Kalubowila, the study examined 102 postmortem cases comprising 68 males and 34 females. The fusion degree of four major cranial sutures; the coronal, sagittal, squamous, and lambdoid was evaluated on both ectocranial and endocranial surfaces using the Meindl & Lovejoy grading system, and data were categorized into four age groups: 21-40, 41-60, 61-80, and 81-100 years. Ethical clearance was requested from the Colombo South Teaching Hospital Ethical Review Committee. Results demonstrated significant sexual dimorphism in skull morphology and revealed earlier fusion of endocranial sutures compared to ectocranial surfaces. Specifically, the lateral ends of the coronal suture fused earlier than its upper segments, and endocranial sagittal suture fusion predominated after 41 years in both males and females, whereas ectocranial sagittal sutures maintained partial fusion throughout life. The endocranial squamous suture was found to be an unreliable indicator for age estimation. Unique observations included suture bones in four specimens and a metopic suture in one 81-year-old individual. The findings suggest that certain cranial sutures can serve as reliable markers for age estimation in the Sri Lankan population; however, others lack distinct age-related features. Consequently, future research is recommended to develop updated and standardized suture grading methods tailored to local forensic requirements.

Keywords: Cranial sutures, Age estimation, Morphology, Forensic anthropology,

1. Introduction

The field of anthropology is broadly categorized into two primary sub-disciplines, biological anthropology and socio-cultural anthropology. Anthropology divides into biological and socio-

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cultural branches. Biological anthropology examines human biology and evolution, including forensic anthropology, which applies biological principles for skeletal identification in legal contexts when other methods are inadequate. Forensic anthropology analyzes skeletal remains to determine age, sex, trauma, and biological profiles, aiding identification when other methods fail. Age estimation employs skeletal growth, dental, pelvic, and cranial suture analysis, crucial for legal and investigative contexts.[1]

Cranial suture fusion is a key forensic age indicator, where fibrous joints progressively fuse over life. Coronal, sagittal, and squamous sutures' fusion patterns enable age estimation through scientific analysis. Early cranial suture fusion studies began with Dwight in 1890, introducing age estimation by suture obliteration.[2] Todd and Lyon's (1925) research detailed endocranial and ectocranial closure patterns, noting slower and more variable ectocranial closure.[3] Brooks (1955) highlighted underestimation in females.[4] Meindl and Lovejoy (1985) refined methods, establishing a widely accepted forensic standard for age estimation from sutures, underscoring their continued significance despite debates.[5]

Forensic anthropology research in Sri Lanka is limited due to a lack of population-specific data and standardized protocols, hindering accuracy and reliability. The country's forensic infrastructure is underdeveloped, compounded by a shortage of trained anthropologists. Addressing these gaps is vital to develop localized, evidence-based frameworks reflecting Sri Lanka's unique biological and cultural diversity. This study aims to analyze coronal, sagittal, squamous, and lambdoid suture fusion patterns at death, evaluate age estimation using international data for local relevance, and identify unique suture features to enhance age estimation accuracy. Strengthening forensic anthropology capacity will improve scientific validity and forensic practices in Sri Lanka, supporting legal and investigative effectiveness in the local context.

2. Materials and Methods

This study is an observational study, followed by a descriptive analysis. A total of one hundred and two (102) cadavers were included in this study. These cadavers were brought for postmortem examinations at the Judicial Medical Officer's Unit, Colombo South Teaching Hospital, Kalubowila, Sri Lanka. Only cadavers with a known age at death were included in this study, focusing on individuals aged 21 years and above. Cadavers with any form of fractures to the skull were excluded from the study. Likewise, specimens exhibiting internal or external wounds in the skull or head region were omitted. Cases involving accidents or trauma affecting the suture lines were also excluded. These criteria were applied to ensure that only skulls with clear and undisturbed suture lines were studied to maintain the reliability of the research.

A data collecting sheet was utilized to monitor 26 suture sites across the Coronal, Sagittal, Lambdoid, and Squamous suture lines from both ectocranial (external) and endocranial (internal) views. The grading of these suture sites was conducted according to the Meindl and Lovejoy suture grading pattern (1985).

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Each autopsy case was assigned a unique specimen number for cross-referencing. During the postmortem examination, incisions were made in the head area, and the outer skin layer around the skull was carefully removed as necessary. After exposing the skull, 'Calvaria' (the upper part of the skull) was removed to begin observation of the sutures according to the criteria outlined in the data sheet. The status of the Coronal, Sagittal, Squamous, and Lambdoid suture lines were observed and scored on the data sheet as fused, partially fused, or non-fused. Although Meindl and Lovejoy's (1985) method originally uses four scoring sites for suture obliteration, this study reduced the scoring to three categories for simplicity. During the removal of Calvaria, if the Lambdoid suture was not included within it, the lower part of the occipital bone was carefully cleaned with a scalpel to clearly observe the Lambdoid suture. Following external observation, the internal patterns of suture fusion were examined after removing the 'Dura' to improve visibility. Additionally, the presence of suture bones or any other special features observed were recorded. Upon completion of observations, skull fragments were returned to the body.

The independent variable in this study was the pattern and degree of fusion of the skull vault sutures, while the dependent variable was the age estimation derived from these fusion patterns. The data sheets collected during the observation of the cadavers were analyzed using descriptive analysis. Photographs taken during the postmortem examinations supplemented the recorded data to provide visual documentation of the suture patterns. This study was limited to cadavers that were recommended for postmortem examinations. Skulls damaged due to accidents, fractures, burns, or diseases were excluded.

3. Results

Out of the total specimens included in this study, 68 were male skulls and 34 were female skulls, indicating a higher representation of males in the sample population (Table 1).

Table 1: Distribution of skull specimens according to gender and age groups

Age Category (Years)	Male Specimens *(n)*	Female Specimens *(n)*
21-40	9	2
41-60	32	11
61-80	19	15
81-100	8	6
Total Number of Specimens for each gender*(n)*	68	34
Total Number of Specimens	*(n)* = 102	

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3.1 Ectocranial coronal suture fusion results of males and females

(Table 2) depicts the pattern of ectocranial left coronal suture fusion in male cranial specimens obtained from postmortem examinations. The left coronal suture was evaluated at three distinct anatomical sites (Figure 1) as C1-Lateral lower, C2-Lateral Middle and C3-Lateral Upper. In the youngest group, 21-40 years, most sutures are either non-fused or partially fused, with very few fully fused sites. The age group of 41-60 shows higher number of partially fused sites in C2 and C3. In contrast, the older age groups, especially 61-80 and 81-100 years show a higher number of fully fused sutures across all three sites. Partial Fusion is visible even at the age of 81-100 years. The site C3 shows higher number of full fusion sites under the three age groups varied from 41 to 100 years.

Table 2: Ectocranial Left Coronal Suture Fusion of the Male Skull Specimens (n = 68)

Age Group (Years)	Ectocranial - Left Coronal Suture (Male)									Total Number of skulls under the Age group (*n*)
	C1			C2			C3			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	1	5	3	1	7	1	0	8	1	9
41-60	1	11	20	1	26	5	0	30	2	32
61-80	0	9	10	0	17	2	0	16	3	19
81-100	0	2	6	0	5	3	0	5	3	8
										(n) = 68

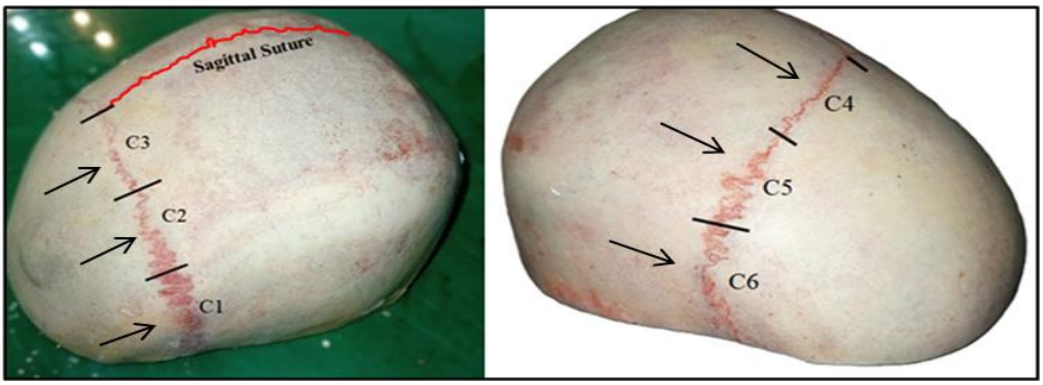

Figure 1: Left and right lateral parts of the ectocranial coronal suture

The right coronal suture was also evaluated at three distinct anatomical sites (C4, C5, and C6) as shown in (Figure 1). Ectocranial right coronal suture fusion of the male skull specimens is shown in the (Table 3). In the 21-40 years group, most sutures are either partially fused or fully fused. Within the total number of 9 skull specimens of this age group, the C5 site shows Non-of the full fusion specimens. Non-fusion is virtually absent in the 41-60, 61-80 and 81-100 years age groups at all sites, suggesting that by the middle age of life, the right coronal suture sites are almost always at least partially fused. The C6 site has the highest number of full fusion of the suture within the age group of 61-100 years.

Table 3: Ectocranial Right Coronal Suture Fusion of the Male Skull Specimens (n = 68)

Age Group (Years)	Ectocranial - Right Coronal Suture (Male)									Total Number of skulls under the Age group *(n)*
	C4			C5			C6			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	8	1	1	8	0	1	5	3	9
41-60	0	30	2	0	27	5	0	12	20	32
61-80	0	16	3	0	18	1	0	9	10	19
81-100	0	5	3	0	5	3	0	2	6	8
										(n) = 68

(Table 4) depicts the pattern of ectocranial left coronal suture fusion in female cranial specimens obtained from postmortem examinations. In the age group of 21-40 years, no full fusion specimens were observed in this sample. The data in the table also shows that the partial fusion of the three suture sites increases by the age gets older. Even though the C1 site fuses at the age of 61-80 years, still the C2 and C3 sites of this sample have the dominance in partial fusion stage. After 81 years of age no non-fusion specimens could be recognized within this sample. Partial fusion is observed in all age groups up to 81-100 at C1, and in the 41-60 age group at C2. It is absent at C2 and C3 for ages 61-80 and 81-100.

Table 4: Ectocranial Left Coronal Suture Fusion of the Female Skull Specimens (n = 34)

Age Group (Years)	Ectocranial - Left Coronal Suture (Female)									Total Number of skulls under the Age group *(n)*
	C1			C2			C3			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	1	1	0	2	0	0	0	2	0	2
41-60	3	6	2	2	9	0	0	11	0	11
61-80	1	4	10	1	11	3	0	11	4	15
81-100	0	2	4	0	4	2	0	5	1	6
										(n) = 34

Table 5: Ectocranial Right Coronal Suture Fusion of the Female Skull Specimens (n = 34)

Age Group (Years)	Ectocranial - Right Coronal Suture (Female)									Total Number of skulls under the Age group *(n)*
	C4			C5			C6			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	2	0	2	0	0	1	1	0	2
41-60	0	11	0	2	9	0	3	6	2	11
61-80	0	12	3	1	11	3	1	10	4	15
81-100	0	5	1	0	5	1	0	2	4	6
										(n) = 34

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(Table 5) depicts the pattern of ectocranial right coronal suture fusion in female cranial specimens obtained from postmortem examinations. The first age group, 21-40 years, does not show any sign of full fusion in any of the suture sites. When it comes to the 41-60 years age group, partial fusion increases in all three sites. Except for the C6 suture site during 81-100 years, other age groups show dominance in partial fusion throughout the time. No specimens were observed that are non-fusion within the C4 site. C6 shows the first site to be fully fused. It shows that according to the sample of this study the full fusion of the ectocranial right coronal suture of the female specimens begins nearly around 41-60 years from the C6 suture site. Some key trends are; in C4, partial fusion can be seen featuring for a long time and full fusion can be observed only in older groups. C5, gradual progression of non-fusion can be seen in younger age groups while partial fusion can be seen in middle and older ages. C6, full fusion becomes dominant only in this suture site after the age passes 81 years.

Figure 2: Coronal suture fusion. (a) Fully fused coronal suture of a 53 year old male specimen, (b) Left coronal suture fusion of a 56 year old male specimen, (c) Left coronal suture fusion of a 55 year old male specimen with C1- not fused C-2 not fused and C3- partially fused

3.2 Endocranial coronal suture fusion results of males and females

The endocranial right coronal suture was evaluated at three distinct anatomical sites (C7, C8, and C9) while the endocranial left coronal suture was evaluated at three distinct anatomical sites (C10, C11, and C12).

Table 6: Endocranial Right Coronal Suture Fusion of the Male Skull Specimens (n = 68)

Age Group (Years)	Endocranial - Right Coronal Suture (Male)									Total Number of skulls under the Age group *(n)*
	C7			C8			C9			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	3	6	0	3	6	0	6	3	9
41-60	0	1	31	0	3	29	0	6	26	32
61-80	0	0	19	0	1	18	0	1	18	19
81-100	0	1	7	0	1	7	0	1	7	8
										(n) = 68

Table 7: Endocranial Left Coronal Suture Fusion of the Male Skull Specimens (n = 68)

Age Group (Years)	Endocranial - Left Coronal Suture (Male)									Total Number of skulls under the Age group *(n)*
	C10			C11			C12			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	6	3	0	3	6	0	3	6	9
41-60	0	6	26	0	3	29	0	1	31	32
61-80	0	1	18	0	1	18	0	0	19	19
81-100	0	1	7	0	1	7	0	1	7	8
										(n) = 68

(Table 6) depicts the pattern of endocranial right coronal suture fusion in male cranial specimens obtained from postmortem examinations. After 41 years, the endocranial coronal suture fuses in most of the skull specimens. No specimens were found with non-fusion grades in all three suture sites. All three suture sites show higher number of full fusion sites within the 4 age groups while

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only having a several partial fusion sites. Within the last age group of 81-100 years there is only one specimen with partial fusion that can be seen in all three sites.

(Table 7) depicts the pattern of endocranial left coronal suture fusion in male cranial specimens obtained from postmortem examinations. Partial fusion is most prominent in 21-40 and 41-60 years. When it comes to the age period of 61-80 years, it can be identified that the fusion of the endocranial left coronal suture sites are nearly completed. Within 81-100 years, the full fusion is can be seen as a dominant trait.

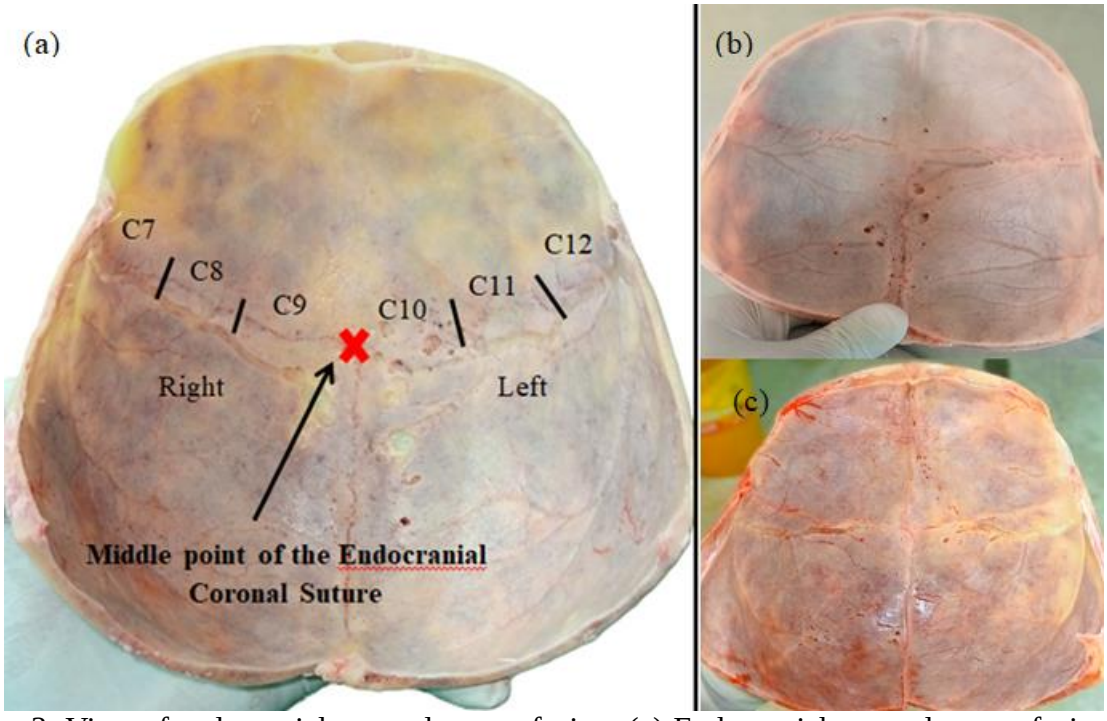

Figure 3: View of endocranial coronal suture fusion. (a) Endocranial coronal suture fusion sites of a 64 year old male specimen (b) Endocranial coronal suture all sites are partially fused of a 29 year old male specimen (c) Endocranial coronal suture C9 and C10 sites are partially fused of an 81 year old female specimen

Table 8: Endocranial Right Coronal Suture Fusion of the Female Skull Specimens (n=34)

Age Group (Years)	Endocranial – Right Coronal Suture (Female)									Total Number of skulls under the Age group *(n)*
	C7			C8			C9			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	1	1	0	1	1	0	1	1	2
41-60	0	1	10	0	1	10	0	3	8	11
61-80	0	0	15	0	0	15	0	1	14	15
81-100	0	0	6	0	0	6	0	1	5	6
										(n) = 34

Table 9: Endocranial Left Coronal Suture Fusion of the Female Skull Specimens (n = 34)

Age Group (Years)	Endocranial – Left Coronal Suture (Female)									Total Number of skulls under the Age group *(n)*
	C10			C11			C12			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	1	1	0	1	1	0	1	1	2
41-60	0	3	8	0	1	10	0	0	11	11
61-80	0	1	14	0	0	15	0	0	15	15
81-100	0	1	5	0	0	6	0	0	6	6
										(n) = 34

(Table 8) depicts the pattern of endocranial right coronal suture fusion in female cranial specimens obtained from postmortem examinations. Full fusion is dominant in all 3 suture sites under all 4 age groups. A few partial fusion specimens were observed in the C9 suture site other than C7 and C8. Partial fusion was observed after 61 years in the C9 suture site in specimens of 61-80 years age group and 81-100 years age group. Further, the non-fusion states cannot be seen in all three suture sites.

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(Table 9) depicts the pattern of endocranial left coronal suture fusion in female cranial specimens obtained from postmortem examinations. No non-fusion specimens were observed within any of the suture sites at any age period. Full fusion is dominant in all the suture sites when referring to all the age groups. C12 represents the endocranial left coronal suture site of females to be the fusion completed at an early age.

3.3 Ectocranial sagittal suture fusion results of males and females

The Sagittal Suture, located along the midline of the skull, was evaluated at three distinct anatomical sites (S1, S2, and S3) in both males and females.

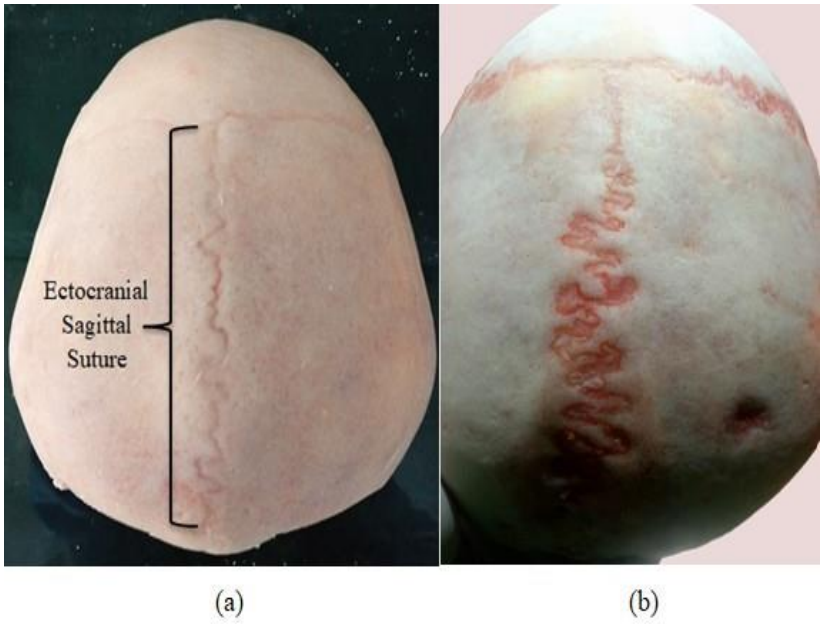

Figure 4: Ectocranial sagittal suture fusion (a) Ectocranial sagittal suture fusion of a 75 year old male specimen (b) Ectocranial sagittal suture fusion of a 31 year old male specimen

Table 10: Ectocranial Sagittal Suture fusion in male specimens (n = 68)

Age Group (Years)	Ectocranial Sagittal Suture (Male)									Total Number of Skulls under the Age Group *(n)*
	S1			S2			S3			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	9	0	2	7	0	2	7	0	9
41-60	0	26	6	1	24	7	1	20	11	32
61-80	0	16	3	0	14	5	0	11	8	19
81-100	0	7	1	2	4	2	2	2	4	8
										(n) = 68

Table 11: Ectocranial Sagittal Suture fusion in female specimens (n = 34)

Age Group (Years)	Ectocranial Sagittal Suture (Female)									Total Number of Skulls under the Age Group *(n)*
	S1			S2			S3			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	2	0	1	1	0	1	1	0	2
41-60	1	8	2	1	9	1	2	8	1	11
61-80	0	9	6	1	10	4	1	10	4	15
81-100	0	6	0	0	4	2	0	4	2	6
										(n) = 34

(Table 10) depicts the pattern of ectocranial sagittal suture fusion in male cranial specimens obtained from postmortem examinations. Non-fusion was not observed at S1 in any age group. The Partial fusion can be seen dominating throughout the suture sites S1, S2 and S3. Skull specimens with non-fusion sites were observed at S2 and S3 resulting that those sites take time to start the fusion process. The first complete fusion at all three suture sites was observed in the 41-60 years age group.

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(Table 11) depicts the pattern of ectocranial sagittal suture fusion in female cranial specimens obtained from postmortem examinations. A dominance of the partial fusion can be seen in all three suture sites of the female skulls. Compared to the non-fusion sites, all three suture sites present a progressive trend on increasing partial fusion of the female skull specimens. The S1 under the 81-100 year age group does not show any specimens that have acquired full fusion and that shows that the fusion of S1 takes time compared to the S2 and S3 of female skull specimens. However S1 shows full fusion sites in middle ages. Full fusion sites were first observed within the 41-60 years age group and can be seen increasing throughout the age develops.

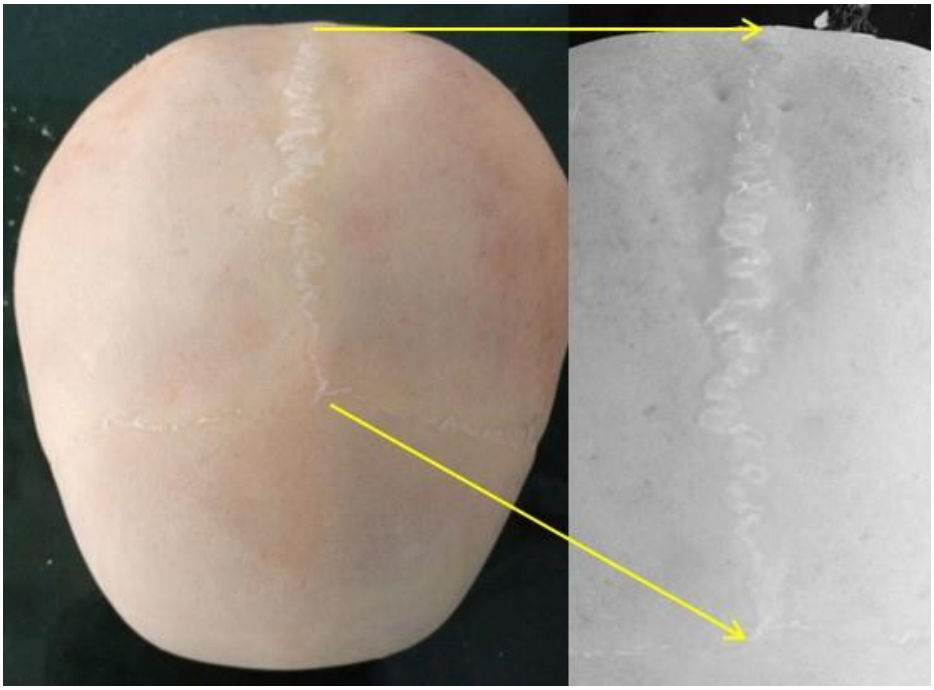

Figure 5: Ectocranial sagittal suture fusion of a 96 year old female specimen – partial fusion sites can be observed on all the sagittal suture sites (S1, S2 and S3)

3.4 Endocranial sagittal suture fusion results of males and females

The Ectocranial sagittal suture, located opposite to the ectocranial sagittal suture of the skull, was evaluated at three distinct anatomical sites (S4, S5 and S6)) in both males and females.

Table 12: Endocranial Sagittal Suture fusion in male specimens (n = 68)

Age Group (Years)	Endocranial Sagittal Suture (Male)									Total Number of Skulls under the Age Group *(n)*
	S4			S5			S6			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	7	2	0	5	4	0	4	5	9
41-60	0	6	26	0	5	27	0	3	29	32
61-80	0	1	18	0	1	18	0	1	18	19
81-100	0	1	7	0	1	7	0	0	8	8
										(n) = 68

(Table 12) depicts the pattern of endocranial sagittal suture fusion in male cranial specimens obtained from postmortem examinations. A critical finding of this study is the complete absence of non-fusion in all examined sections of the endocranial sagittal suture, specifically the S4, S5, and S6 regions across all male specimens aged 21 to 100 years. This suggests that these endocranial sagittal suture regions play a significant role in achieving complete fusion at relatively earlier ages. When referring to the sites presenting full fusion, S6 consistently demonstrates the highest rate of full fusion, particularly in the younger and middle age groups. In the 21-40 year group, S6 has the highest full fusion count (n = 5) compared to partial fusion count (n = 4) of the same age group. This trend continues into the 41-60 year group, where S6 shows the highest full fusion (n = 29). These findings about the S6 site suggest that it can be identified as suture site to determinate age of a person. A rapid transition from partial to full fusion can also be studied using the data set of the table 11. While partial fusion is present within the 21-40 year group, its counts significantly decreases and become lower by the 61-80 year age group (n = 1 for S4, S5, S6) and non-existent for S6 in the 81-100 group.

Table 13: Endocranial Sagittal Suture fusion in female specimens (n = 34)

Age Group (Years)	Endocranial Sagittal Suture (Female)									Total Number of Skulls under the Age Group *(n)*
	S4			S5			S6			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	1	1	0	1	1	0	1	1	2
41-60	0	2	9	0	2	9	0	1	10	11
61-80	0	0	15	0	0	15	0	0	15	15
81-100	0	1	5	0	0	6	0	0	6	6
										(n) = 34

(Table 13) depicts the pattern of endocranial sagittal suture fusion in female cranial specimens obtained from postmortem examinations. Non-fusion cases were completely absent in all endocranial points of the sagittal suture across all age groups. The dominance of specimens with full fusion can be seen in all age groups while a rapid progression of full fusion within the development of age. The specimens with Partial fusion sites are visible during the earlier ages of life (21-60 years). The last age group, 81-100 years, presents a one specimen which shows partial fusion in S4 and it provides the evidence that particular site might have a lower speed on fusion process.

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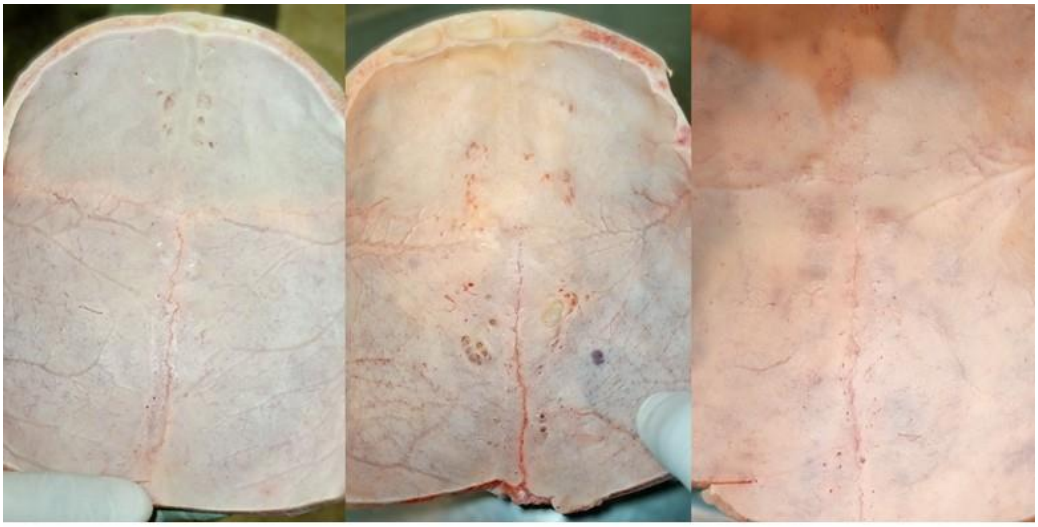

(a) (b) (c)

Figure 6: Endocranial sagittal suture fusion (a) Endocranial sagittal suture fusion of a 24 year old male specimen (b) Endocranial sagittal suture fusion of a 39 year old male specimen (c) Endocranial sagittal suture fusion of a 47 year old male specimen

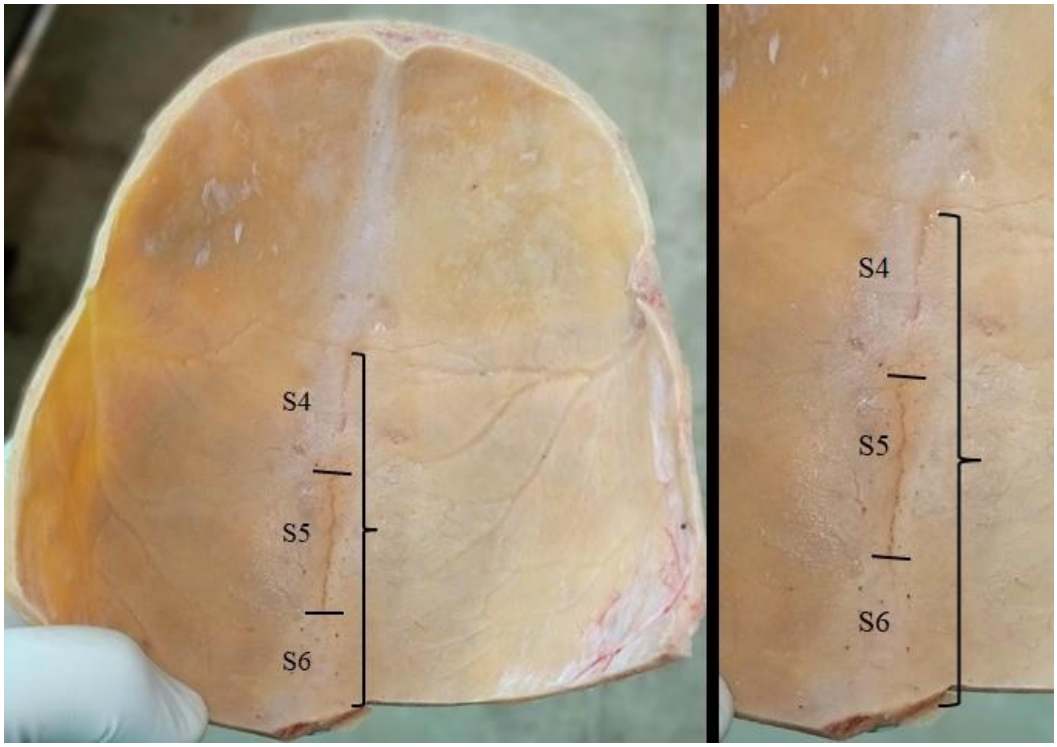

Figure 7: Endocranial sagittal suture fusion of a 55 year old male specimen with S6 (Posterior segemnt of the endocranial sagittal suture) having a full fusion site with the other two are having partial fusion

3.5 Ectocranial squamous suture fusion results of males and females

The Ectocranial squamous suture, located at the two lateral ends of the skull, was evaluated as the left squamous suture and right squamous suture in males and females.

Table 14: Ectocranial Squamous suture fusion of male specimens (n = 68)

Age Group (Years)	Ectocranial Squamous (Male)						Total Number of Skulls under the Age Group *(n)*
	Squamous (L)			Squamous (R)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	5	4	0	5	4	9
41-60	0	10	22	0	10	22	32
61-80	0	1	18	0	1	18	19
81-100	0	1	7	0	1	7	8
							(n) = 68

Table 15: Ectocranial Squamous Suture Fusion of Female Specimens (n = 34)

Age Group (Years)	Ectocranial Squamous (Female)						Total Number of Skulls under the Age Group *(n)*
	Squamous (L)			Squamous (R)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	1	0	1	1	0	1	2
41-60	1	2	8	1	2	8	11
61-80	0	2	13	0	2	13	15
81-100	0	1	5	0	1	5	6
							(n) = 34

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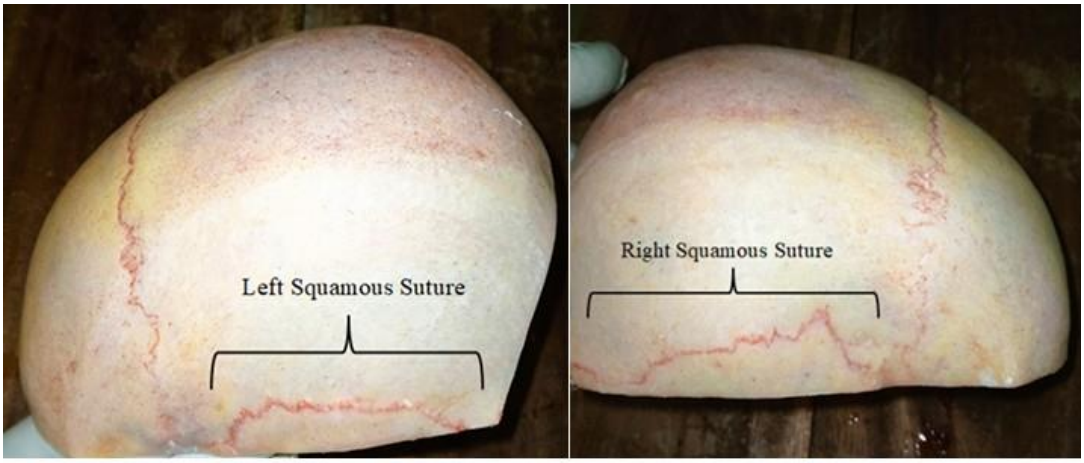
(a) (b)

Figure 8: Ectocranial squamous suture fusion (a) Ectocranial left squamous suture fusion of a 57 year old female specimen – Fully fused (b) Ectocranial right squmous suture fusion of a 57 year old female specimen – Fully fused



(a) (b)

Figure 9: Ectocranial squamous suture fusion (a) Partially fused ectocranial left squamous suture of a 60 year old male specimen (b) Partially fused ectocranial right squamous suture of a 60 year old male specimen

(Table 14) depicts the pattern of ectocranial squamous suture fusion in male cranial specimens obtained from postmortem examinations. Partial fusion is observed primarily in younger age groups, while full fusion becomes increasingly dominant in older age groups. It can be also seen that non-fusion points are absent in all the age groups. It can be identified that by the age group of 61-80 years range, ectocranial squamous sutures are almost entirely fully fused.

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(Table 15) depicts the pattern of ectocranial squamous suture fusion in female cranial specimens obtained from postmortem examinations. According to the sample of specimens (*n* = 34), the left and right squamous sutures shows a progressive fusion pattern with age. Partial fusion is observed across various age groups but decreases with age. Within the 41-60 years age group, the majority (8 out of 11 specimens) are in 'Full Fusion'. After 61 years of age it increases much more. 'Full Fusion' gradually increases in prevalence, becoming the dominant state in older age groups.

3.6 Endocranial squamous suture fusion results of males and females

The Endocranial squmous suture was evaluated as the right squamous suture and left squamous suture in males and females.

Table 16: Endocranial Squamous Suture Fusion of Male Specimens (n = 68)

Age Group (Years)	Endocranial Squamous (Male)						Total Number of Skulls under the Age Group *(n)*
	Squamous (R)			Squamous (L)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	0	9	0	0	9	9
41-60	0	0	32	0	0	32	32
61-80	0	0	19	0	0	19	19
81-100	0	0	8	0	0	8	8
							(n) = 68

(Table 16) depicts the pattern of endocranial squamous suture fusion in male cranial specimens obtained from postmortem examinations. The endocranial squamous sutures show a consistent pattern of 'Full Fusion' across all examined age groups.

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Table 17: Endocranial Squamous Suture Fusion of Female Specimens (n = 34)

Age Group (Years)	Endocranial Squamous (Female)						Total Number of Skulls under the Age Group (*n*)
	Squamous (R)			Squamous (L)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	0	2	0	0	2	2
41-60	0	0	11	0	0	11	11
61-80	0	0	15	0	0	15	15
81-100	0	0	6	0	0	6	6
							(n) = 34

(a) (b) (c) (d)

Figure 10: Endocranial squamous suture with full fusion (a) 23 year old male specimen (b) 24 year old male specimen (c) 39 year old male specimen (c) 56 year old male specimen

(Table 17) depicts the pattern of endocranial squamous suture fusion in female cranial specimens obtained from postmortem examinations. The two suture sites also shows full fusion across all the age groups. Non of the 'Partial' or 'Non fusion' sites were observed out of the selected sample of the study.

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(a) (b) (c)

Figure 11: Endocranial squamous suture with full fusion (a) 43 year old female specimen (b) 57 year old female specimen (c) 96 year old female specimen

3.7 Ectocranial lambdoid suture fusion results of males and females

Lambdoid Suture is located at the back of the skull with related to 'lambda'. This suture was evaluated as the left lambdoid suture and right lambdoid suture on males and females.

Table 18: Ectocranial Lambdoid Suture Fusion of Male Specimens (n = 68)

Age Group (Years)	Ectocranial Lambdoid (Male)						Total Number of Skulls under the Age Group *(n)*
	Lambdoid (L)			Lambdoid (R)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	2	7	0	2	7	0	9
41-60	1	24	7	1	23	8	32
61-80	0	7	12	0	7	12	19
81-100	1	1	6	1	1	6	8
							(n) = 68

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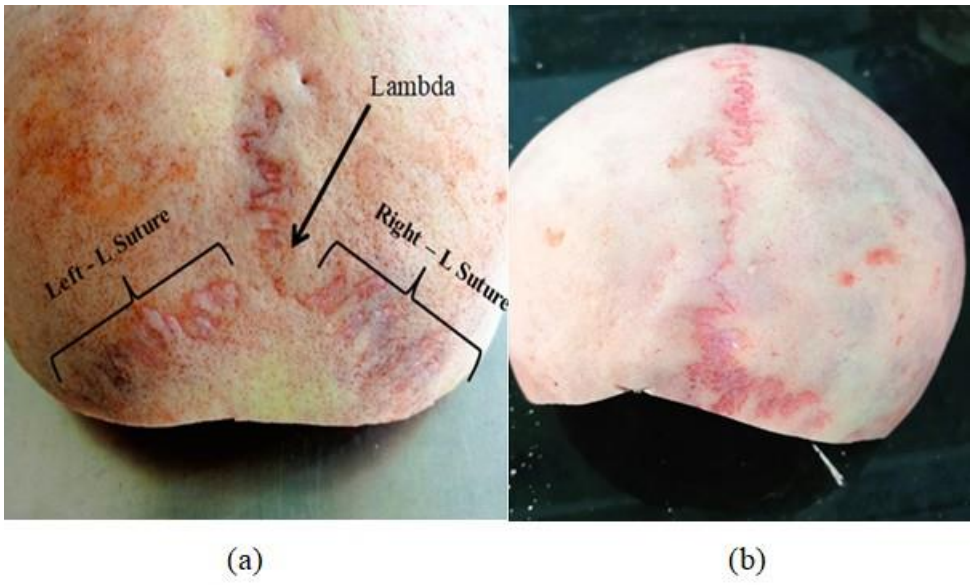

Figure 12: Ectocranial lambdoid suture (a) Ectocranial lambdoid suture of a 57 year old male specimen (b) Ectocranial lambdoid suture of a 46 year old male

Table 19: Ectocranial Lambdoid Suture Fusion of Female Specimens (n = 34)

Age Group (Years)	Ectocranial Lambdoid (Female)						Total Number of Skulls under the Age Group *(n)*
	Lambdoid (L)			Lambdoid (R)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	2	0	0	2	0	0	2
41-60	1	9	1	1	9	1	11
61-80	0	11	4	0	11	4	15
81-100	0	5	1	0	5	1	6
							(n) = 34

(Table 18) depicts the pattern of ectocranial lambdoid suture fusion in male cranial specimens obtained from postmortem examinations. Between 21 and 40 years of age, the majority of specimens show partial fusion, with seven out of nine specimens exhibiting this, while two specimens still show non-fusion. None of the skulls in this age group display complete fusion of

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both the left and right lambdoid sutures. From 41 to 60 years of age, partial fusion continues to be highly common at both suture sites. After 61 years of age, full fusion becomes predominant in this sample, and after 81 years, it is clearly dominant. However, the table data display that non-fusion and partial fusion can still persist into very old age, indicating that this suture surface may not consistently achieve full fusion across all individuals.

Figure 13: Ectocranial lambdoid suture with an identical feature of the left lambdoid is fused and right lambdoid with 'Partial Fusion'.

(Table 19) depicts the pattern of ectocranial lambdoid suture fusion in female cranial specimens obtained from postmortem examinations. The ectocranial lambdoid sutures in female specimens show a very slow and incomplete fusion pattern. In the 21 to 40 years age group, only two skull specimens were included in the study, and both show non-fusion across the left and right lambdoid sutures. In the 41 to 60 years age group, the majority of the specimens, nine out of eleven, exhibit partial fusion, while only one specimen shows full fusion. Partial fusion predominates across all older age groups, including the oldest group of 81 to 100 years. Full fusion is rare but does occur occasionally.

3.8 Endocranial lambdoid suture fusion results of males and females

The endocranial lambdoid suture was evaluated as the right lambdoid suture and the left lambdoid suture.

Table 20: Endocranial Lambdoid Suture Fusion of Male Specimens (n = 68)

Age Group (Years)	Endocranial Lambdoid (Male)						Total Number of Skulls under the Age Group *(n)*
	Lambdoid (R)			Lambdoid (L)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	1	8	0	1	8	9
41-60	0	1	31	0	1	31	32
61-80	0	0	19	0	0	19	19
81-100	0	0	8	0	0	8	8
							(n) = 68

(Table 20) depicts the pattern of endocranial lambdoid suture fusion in male cranial specimens obtained from postmortem examinations. Although the endocranial lambdoid suture is not visible to the naked eye, its fusion pattern exhibits distinct trends that assist in age estimation. Partial fusion is observed exclusively in specimens aged between 21 and 60 years. Beyond 61 years, all specimens, including nineteen individuals aged 61 to 80 years and eight individuals aged 81 to 100 years, exhibit complete fusion. Consequently, the endocranial lambdoid suture in males demonstrates an early and comprehensive fusion pattern.

(Table 21) depicts the pattern of endocranial lambdoid suture fusion in female cranial specimens obtained from postmortem examinations. The data table suggest that the endocranial lambdoid sutures in female specimens tend to fuse very early and completely. After 21-40 years age group, all skulls specimens from 41 years onwards are fully fused.

Table 21: Endocranial Lambdoid Suture Fusion of Female Specimens (n = 34)

Age Group (Years)	Endocranial Lambdoid (Female)						Total Number of Skulls under the Age Group *(n)*
	Lambdoid (R)			Lambdoid (L)			
	Non Fusion	Partial Fusion	Full Fusion	Non Fusion	Partial Fusion	Full Fusion	
21-40	0	1	1	0	1	1	2
41-60	0	0	11	0	0	11	11
61-80	0	0	15	0	0	15	15
81-100	0	0	6	0	0	6	6
							(n) = 34

3.9 Observation of special morphological features in the calvaria

Beyond the primary investigation into skull vault suture fusion patterns for age estimation, this research encompassed a detailed examination of additional morphological features encountered during the skull vault suture observation.

3.9.1 Sutural bones/ Wormian bones

During postmortem examination and skull vault cleaning, four (4) specimens were identified with wormian bones, within the total sample. Their structures varied considerably between individuals, indicating low incidence and marked anatomical variability.

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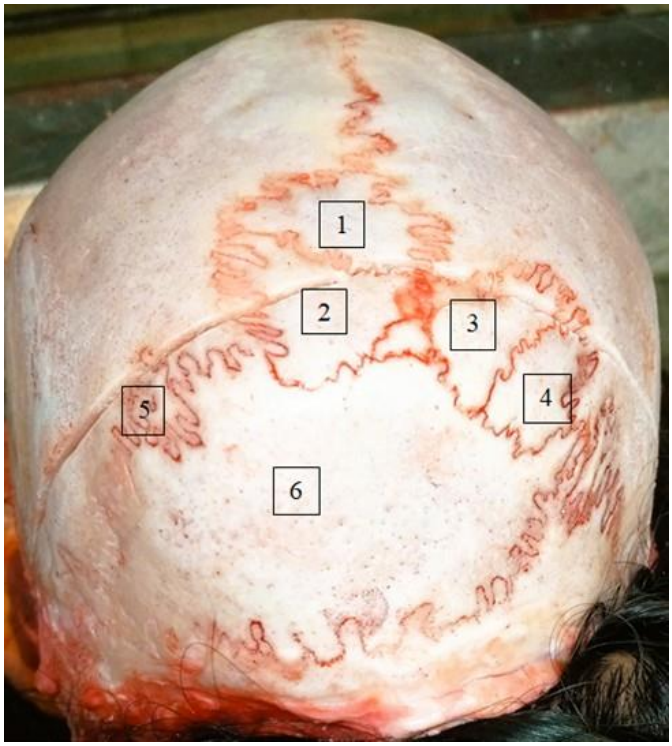

Figure 14: 6 wormian bones in a 24 year old female specimen

(Figure 14) depicts a 24 year old female specimen which was examined to study suture fusion patterns. Most of the suture sites showed either 'Non fusion' or only 'Partial fusion', indicating that the sutures were still largely open at this age. Notably, six wormian bones of varying sizes were identified, one in the parietal bone (1), one in lambda (2), 4 in occipital bone (3-4-5-6).

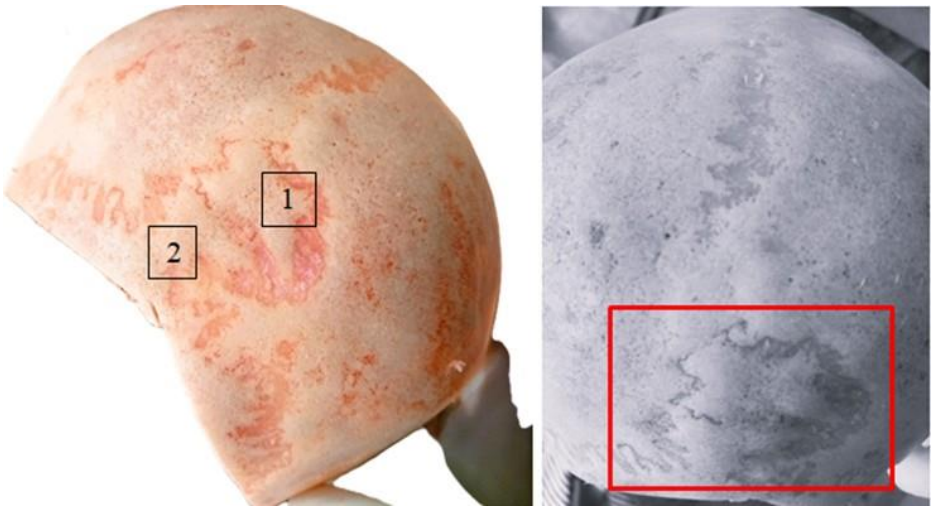

Figure 15: 2 wormian bones in a 57 year old male specimen

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(Figure 15) depicts a male skull specimen of a 57 year old male and 2 wormian bones were observed located in the posterior region (occipital bone) of the skull. The margins of the suture bones were sighted with broken suture lines which are partial fusion sites in common.

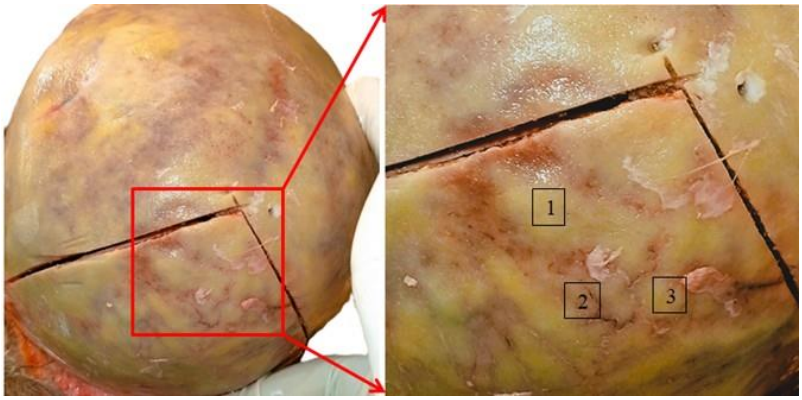

Figure 16: 3 wormian bones in a 89 year old female specimen

(Figure 16) depicts a female skull specimen of an 89 year old female. The suture bones are not clearly visible at the first glance but the margins spread around the position of lambda shows 3 suture bones. The margins of the suture bones slightly fused but some of them are visible.

Figure 17: 2 wormian bones (a) wormian bone in the ectocranial left lambdoid suture (b) wormian bone in the ectocranial left lambdoid suture

(Figure 17) depicts a female skull specimen of a 72 year old female. Two suture bones were sighted, one in the ectocranial left lambdoid suture and the other in the ectocranial right lambdoid suture. The suture bone of the Left lambdoid suture was a small one compared to the one in the right lambdoid suture.

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3.9.2 Metopic Suture

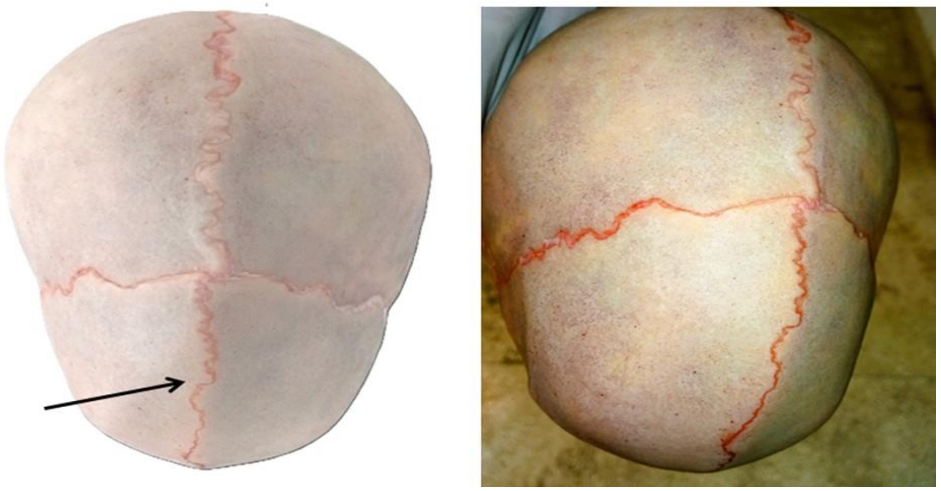

Figure 18: Metopic suture observed in a 81 year old female specimen

(Figure 18) depicts an 81 year old female specimen. A metopic suture was identified in this specimen. This was the only suture observed, aside from the four principal cranial sutures. The presence of a visible metopic suture at this advanced age is noteworthy, as it is uncommon for this suture to remain non-fused and discernible in elderly individuals.

4. Discussion

4.1 Distribution of age and gender of the skull specimens

The present study involved the examination of 102 skull specimens obtained from cadavers at the Colombo South Teaching Hospital, Kalubowila, Sri Lanka. The specimens were collected from the Judicial Medical Officer (JMO) section during postmortem examinations and categorized by gender and age (*Female n = 34, Male n = 68*). The male skull specimens were taken to the study more than the female ones. Between 21-60 years there are 51 male cadavers studied and the reason for the high number of males in this age group seems to be a common thing. This could be attributed to demographic and societal factors, including higher male mortality rates in certain age groups or causes of death that lead to postmortem examinations. The gender distribution is important as it allows for comparative analysis of sexual dimorphism in cranial morphology, which is critical for forensic identification and anthropological research. Skull morphology can vary significantly between males and females, and it can even make an impact on the cranial suture fusion process.

Several investigations have reported findings consistent with this matter such as follows: Rajitha Sivakumaran has authored an article on ‘The Impact of Sex and Ancestry on Cranial Sutures in the Hamann-Todd Collection’ and he highlight significant sex-based differences in coronal and lambdoid sutures, with females showing greater progression of suture closure than males, though

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the sagittal suture showed less sex difference.[6] A.G. Vijay Kumar states that there is a close association between suture closure and sex determination and also the suture closure contribute to sex determination of unidentified skeletal remains.[7] In summary, the study's gender distribution reflects common forensic patterns and underscores the importance of population-specific data in cranial analysis. The predominance of male skulls offers a robust dataset for male cranial characteristics, while the female skulls provide a necessary comparative framework. These findings will aid forensic experts and anthropologists in improving identification accuracy and understanding cranial morphology.

4.2 Key findings on the fusion patterns of the skull vault sutures

4.2.1 Endocranial suture fusion occurs earlier than the ectocranial suture fusion

The present study observed that endocranial suture fusion initiates and progresses earlier than ectocranial suture fusion. This finding is consistent with several previous investigations which have reported a similar pattern of earlier fusion on the endocranial (inner surface) of cranial sutures compared to the outer ectocranial (outer surface). Laxmi Rawat in his study on the cranial vault suture fusion for estimation of age proves that the closure of sutures start endocranially, followed by ectocranial suture and he also state that the process of suture closure is more speedy in the endocranial sutures than the sutures that are in the ectocranial.[8] In his study, he conclude that the estimation of age of the study subjects will be appropriate by the suture closure of the endocranial surface in comparison to the ectocranial fusion. A.G. Vijay Kumar and few other scholars also prove the idea by their study on fusion of skull vault sutures in relation to age by stating that all sutures closure starts earlier endocranially than ectocranially.[9] So it can be identified that the pattern of sututre fusion happens earlier on the inner surface of the skull than the outer surface of the skull.

4.2.2 The lateral ends of the ectocranial coronal suture (C1 & C6) complete fusion earlier than the other suture sites of the coronal suture

In this study, Tables 2 and 3 present the suture fusion patterns of the ectocranial coronal suture in male specimens, while Tables 6 and 7 display the corresponding patterns in female specimens. In both males and females, the lateral parts of the suture sites, identified as C1 and C6, show the highest number of full fusion sites. This indicates that these lateral regions are the most significant areas for complete fusion in the ectocranial coronal suture across sexes. It also indicates that the two sites fuse earlier than other segments (C2, C3, C4, C5) in the coronal suture. Many other studies also support this idea: According to Laxmi Rawat, the lower (lateral) parts of the coronal suture start fusion earlier and progress faster than the upper parts of the coronal suture.[8] Another study on cranial sutures signify that, the significant correlations between age and fusion stages, indicating that fusion initiates and progresses earlier at the lateral (lower) parts of the coronal suture compared to the upper parts of the coronal suture.[9] These two autopsy based studies prove that the fusion of the two lateral parts of the skull vault sutures happens earlier than the other upper segments of the coronal suture as the results which are gained in this study. Another study done by using postmortem CT scans have found that the

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coronal suture starts to fuse earlier at the lateral parts before the middle segments of the coronal suture.[10] These studies support the fact that the fusion of coronal suture occurs from the lateral segments to the upper segments as the resulted data found in this study.

4.2.3 Endocranial sagittal suture completion dominance after 41 years

The data from Table 11 and Table 13 collectively demonstrate that the endocranial sagittal suture exhibits a sex-specific pattern of fusion, with males completing fusion at the suture sites S4, S5, and S6 by around 41 years of age, while females tend to reach similar completion from 41 years onward. This indicates that the endocranial sagittal suture plays a dominant role in the timing of full fusion, as it fuses faster than other cranial sutures. Multiple studies support this observation, showing that endocranial sagittal suture closure begins relatively early:

Hitesh Chawla explains that the sagittal sutures obliterate earlier than the coronal and lambdoid. His study also demonstrates that the fusion of endocranial sagittal is governed by the phenomenon of lapsed union, which indicates that the inner surface sutures fuse sooner and more predictably.[11] According to a study on the estimation of age from macroscopic sagittal suture closure in an Indian population, both endocranial and ectocranial sagittal sutures starts closure at the age of 20-29 and the completion can even go until 70 years of age. This study challenge the findings of this study as it highlights the completion time of the sagittal suture varies until the older ages.[12]

However, a web article supports the findings of this study by illustrating the reasons for the early fusion of the sagittal suture. It indicates that the process of 'Intramembranous Ossification' which occurs on the sagittal suture is the reason to the early fusion of the suture sites.[13] The sagittal suture, located between two parietal bones along the midline of the skull is formed by this process and the early closure of the suture is related to the development pattern of this process. It highlights that the endocranial sagittal fusion happens earlier and the ectocranial fusion occurs gradually to protect the brain in adulthood.

4.2.4 Ectocranial sagittal suture maintain partial fusion for a long duration of life

The observations of the study reveal a dominance of partial fusion of the ectocranial sagittal suture across a wide age range from 21 to 100 years in both males and females. This pattern is consistent with findings from multiple studies, which report that the sagittal suture, particularly at the ectocranial surface, often remains partially fused rather than fully closed even at advanced ages. Specifically, suture sites (S1, S2, and S3) exhibit similar gradual fusion patterns, indicating a slow and progressive completion of sagittal suture closure over many decades.

According to the 'macroscopic study of closure of sagittal suture', ectocranial sagittal suture closure is slower and it is often partially fused while being visible for many years.[12] His study also proves that the different segments of the sagittal suture closure occur at different age periods of the life. Jangjetriew suggest that the ectocranial sutures do not fuse at the early ages of life. He

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also state that the ectocranial suture fusion reflects slower and more variable compared to endocranial suture fusion.[14] In 2020, Michael K. Boyajian proposed that the partial fusion in cranial sutures, including sagittal suture, persists in a significant proporation and his study showed a notable rate of partial fusion on sagittal suture throughout different age periods supporting the idea.[15] Luke Soliman argues that although there is an association between increasing adult age and gradual closure of the sagittal, coronal, lambdoid sutures of the skull, most sutures remain partial due to various reasons.[16] According to Anupam Johry, the sagittal sutures of the skull exhibit highly erratic patterns, making them unreliable for estimating the age of a deceased individual.[17] The unpredictable nature of sagittal suture fusion means that it neither serves as a dependable indicator for age determination nor provides substantial supportive evidence in forensic analysis. Furthermore, the completion of fusion in these sutures tends to occur much later in life, often extending into older ages, which further complicates their use as a chronological marker. This variability underscores the limitations of relying on sagittal sutures alone for accurate age estimation in forensic and anthropological contexts. However all of these studies prove the core idea, that the fusion of the sagittal suture on the outer surface takes time and it has so many variations ectocranially.

4.2.5 Endocranial Sagittal Suture's posterior segment (S6) can be a reliable indicator on estimating older ages

The endocranial sagittal suture site S6 appears to be a reliable indicator for estimating older ages, based on the study's findings. It was observed that no partial fusion occurs in males after 81 years and no partial fusion in females after 61 years at this site, suggesting that complete fusion at S6 correlates strongly with advanced age. However, this conclusion remains tentative, as it represents an idea derived from the current research and is subject to debate. Other studies have argued against the reliability of sagittal suture closure for precise age estimation. Laxmi Rawat strongly argues that the posterior segment of sagittal suture could not be used as an age indicator of the older age groups and only significant individual variations can be seen.[8]

4.2.6 Endocranial lambdoid suture completion can be supportive in age estimation

The study indicates that endocranial lambdoid suture fusion typically occurs during middle age, with fusion generally completing by around 60 years in males and 40 years in females. This timing aligns with some previous research supporting this critical point, suggesting a sex-related difference in the fusion process. However, despite these observations, a definitive conclusion cannot be drawn, and the idea remains a proposed hypothesis rather than an established fact. A.G.V. Kumar did not gave an exact idea on what is meant by the middle ages but he figured the core point that the lambdoid suture closure tends to complete around middle age, with females generally closing earlier. This idea is proposed by this research and it should be studied furthermore.[7]

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4.2.7 Endocranial squamous suture would be unreliable for age estimation

The results presented in Tables 15 and 17 regarding endocranial squamous suture fusion show a distinct pattern between males and females. In males, there is 100% complete fusion across all age groups, indicating a consistent and uniform closure of the squamous suture endocranially. In contrast, females exhibit only a single case of partial fusion within the 21-40 years age group, with full fusion and no further variation observed in older ages. Despite this apparent uniformity, the fusion of the endocranial squamous suture cannot be considered a reliable main indicator. C.A. Key support the idea by suggesting that the early and often fusion on the endocranial sutures like squamous are unreliable for estimating age, especially on adults. The early complete fusion of the sutures gives no significant traces on identification and as a result of that this issue arises.[18]

5. Conclusion

The present study set out with the primary aim of investigating how skull vault suture fusion patterns can be utilized to estimate the age of deceased individuals. By focusing on the fusion status of four major cranial sutures the coronal, sagittal, squamous, and lambdoid this research sought to identify distinct fusion patterns that correlate with age at death, thereby contributing to forensic and anthropological age estimation methods.

One of the key observations supporting the age estimation process is the earlier fusion of endocranial sutures compared to their ectocranial counterparts. This suggests that the internal surfaces of the skull may provide earlier chronological clues than the outer surfaces, which is a valuable insight for forensic investigations. Specifically, the lateral ends of the ectocranial coronal suture were found to complete fusion earlier than other coronal suture sites, indicating that these locations might serve as more precise markers for estimating younger adult ages. Additionally, the endocranial sagittal suture showed a notable pattern of completion dominance after 41 years, and the endocranial lambdoid suture fusion also demonstrated potential to support age estimation. Among these, the posterior segment of the endocranial sagittal suture emerged as a particularly reliable indicator for estimating older ages.

The study also identified several findings that challenge the straightforward use of suture fusion for age estimation. Some of the complicated suture sites were challenging to acquire the necessary aims of this study.

Beyond the standard fusion patterns, the study also encountered special anatomical features that add complexity to age estimation. Notably, suture bones small, irregular ossicles found within sutures and the presence of a persistent metopic suture at 81 years were observed. These features, while not directly related to age estimation, provide important anatomical context and illustrate the diversity of cranial morphology. The occurrence of metopism, although rare in adults, is considered a clinically significant radiological finding and is not classified as pathological. Its

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presence in an elderly individual in this study emphasizes the variability of suture closure and the limitations of relying solely on suture fusion for age determination.

Interpretation of the data also suggests that sex differences influence fusion timing, with females generally exhibiting earlier suture fusion than males. This sexual dimorphism in cranial development is consistent with broader biological patterns and must be accounted for when applying fusion data to age estimation. However, the study also acknowledges that some specimens do not conform to expected patterns due to natural variation or underlying medical conditions, which further complicates the establishment of universal age markers.

6. Recommendations

The study faced several limitations that impact the generalizability and strength of its conclusions. The present study was done as a preliminary study. The sample size was relatively small, with 102 cadavers examined, which restricts the statistical power and may not capture the full range of population variability. Additionally, there was an imbalance in the sex distribution, with 68 male and 34 female specimens, which could bias sex-specific findings. These factors highlight the challenges of conducting forensic research with limited and uneven samples. Furthermore, some traditional theoretical models, such as the Meindl-Lovejoy method, found to be outdated in light of the prolonged fusion times observed in this study, suggesting that age estimation frameworks need continuous refinement based on new empirical evidence.

To improve the accuracy and reliability of age estimation using skull vault sutures, it is essential to employ more precise and advanced examination techniques. Moving beyond naked eye observations, the integration of modern imaging technologies and postmortem analytical tools can offer a more detailed assessment of suture fusion patterns. This will enable better visualization of subtle fusion stages and anatomical variations, thereby enhancing the achievement of research objectives.

Future research should prioritize obtaining a balanced sample with equal representation of males and females. Such a balanced distribution is critical for valid sex-based comparisons and for understanding gender-specific differences in fusion patterns. Ensuring a well-distributed sample will increase the robustness of age estimation and make conclusions more broadly applicable.

The traditional Meindl and Lovejoy suture grading system appears limited when considering recent findings, including those from this study. There is an urgent need to develop a refined grading method that captures the complexity and variability of skull vault suture fusion more accurately. This updated system should incorporate modern scientific knowledge and technological advances to improve the precision of age estimation from cranial sutures.

Additionally, this study was conducted solely at Colombo South Teaching Hospital, which limits the generalizability of the findings. A multi-centered approach involving various regions across

Sri Lanka is recommended for future studies to capture broader population diversity and enhance the applicability of the results nationwide.

Implementing these recommendations will significantly advance forensic anthropology and bio-archaeology by refining age estimation methodologies and increasing the interpretative value of cranial suture analysis.

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