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AGE ESTIMATION USING STERNAL END OF CLAVICLE OSSIFICATION ON COMPUTED TOMOGRAPHY (CT SCAN): A POPULATION-BASED STUDY

Original Research

Anwar Ul Haq[1], **Naheed Siddiqui**[1]*
[1]Forensic Medicine and Toxicology, Khyber Girls Medical College Hayatabad, Peshawar

Corresponding Author: Naheed Siddiqui, Assistant Professor, Forensic Medicine and Toxicology, Khyber Girls Medical College Hayatabad, Peshawar, naheedsiddiqui@ymail.com

Acknowledgement: The authors express gratitude to the Radiology Departments of Hayatabad Medical Complex Peshawar and Khyber Girls Medical College Peshawar for their support in data collection and imaging analysis.
DOI: https://doi.org/10.71000/a5tkfc22

Conflict of Interest: None Grant Support & Financial Support: None Publication Date: 08-01-2025

ABSTRACT

Background: Age estimation plays a critical role in forensic and clinical medicine, particularly in legal and medico-legal contexts where determining chronological age is essential for criminal responsibility, immigration cases, and unidentified human remains. Skeletal maturation assessments using clavicular ossification have gained prominence due to their reliability beyond adolescence. The medial clavicular epiphysis is one of the last skeletal sites to fuse, making it a crucial anatomical structure for age estimation. Computed tomography (CT) imaging provides high-resolution assessment of ossification stages, reducing interpretative errors associated with conventional radiography.

Objective: This study aimed to evaluate the correlation between medial clavicular ossification stages and chronological age using CT imaging and to develop regression models for age estimation in a defined population.

Methods: A cross-sectional, population-based study was conducted at Hayatabad Medical Complex Peshawar and Khyber Girls Medical College Peshawar between January 2024 and July 2024. A total of 142 individuals (84 males, 58 females) aged 8–30 years were included. High-resolution CT scans with a slice thickness of 1–2 mm were used to assess the sternal end of the clavicle. Ossification stages were classified using a standardized five-stage system. Intra- and inter-examiner reliability was evaluated using the Kappa coefficient. Statistical analyses included t-tests, Spearman's correlation, and multivariate logistic regression to predict chronological age based on clavicular ossification.

Results: The mean age of participants was 21.46 ± 4.97 years. Intra-examiner and inter-examiner reliability assessments yielded Kappa values of 0.854 and 0.753, respectively. Developmental differences between right and left clavicles were not statistically significant in males ($p = 0.08$) or females ($p = 0.41$). Stage 1 ossification was observed as early as 8 years in females and 15–17 years in males. Stage 2 was present between 15 and 20 years in males and between 16 and 18 years in females. Stage 3 occurred within 15–23 years for both sexes. Stage 4 was noted from 19–30 years in females and 20–30 years in males. Complete fusion (Stage 5) appeared at 20–30 years in males and 22–30 years in females. Regression models demonstrated a high coefficient of determination ($R^2 = 0.98$), confirming the predictive accuracy of clavicular ossification for age estimation.

Conclusion: CT imaging proved to be an effective tool for age estimation by providing precise visualization of clavicular ossification stages. The findings support the reliability of medial clavicular fusion as a forensic age marker, emphasizing the need for population-specific reference data. Future studies should incorporate larger sample sizes, particularly younger individuals, to further refine age estimation models for forensic and medico-legal applications.

Keywords: Age determination by skeleton, clavicle, forensic anthropology, ossification, population study, regression analysis, tomography X-ray computed.

INTRODUCTION

Age estimation plays a pivotal role in forensic science and clinical medicine, particularly in legal and medico-legal settings where determining an individual's chronological age is essential for establishing criminal responsibility, verifying immigration claims, and identifying unknown individuals. Various skeletal and dental methods have been utilized for this purpose, with the ossification of the sternal end of the clavicle emerging as a highly reliable indicator, especially in late adolescence and early adulthood (1). Among all bones, the clavicle is the last to complete its ossification process, making it a valuable anatomical structure for age assessment beyond the range typically covered by dental and hand-wrist radiographs (2). The sternal end of the clavicle follows a well-documented sequence of ossification changes, occurring predominantly between 18 and 30 years of age. This prolonged developmental process makes it particularly useful for distinguishing between juveniles and adults, offering forensic and medical professionals a critical tool in age determination. The secondary ossification center at the sternal end usually appears between 16 and 21 years and undergoes gradual fusion until complete ossification, which may extend beyond 25 years (3). Unlike traditional skeletal markers, which lose reliability after early adolescence, clavicular ossification remains a viable indicator during late adolescence and early adulthood (4).

Several imaging modalities have been employed to assess clavicular ossification, including conventional radiography (X-ray), computed tomography (CT), magnetic resonance imaging (MRI), and ultrasonography. While X-ray imaging is widely accessible and cost-effective, it has limitations such as anatomical overlap and lower resolution, which can affect the precision of ossification stage assessment (5). In contrast, CT scans offer superior image clarity and allow for more accurate evaluation of ossification stages. Studies have demonstrated that the classification of the sternal end of the clavicle into distinct ossification stages correlates with chronological age, making it a valuable tool in forensic and clinical applications (6). However, inter-population differences in ossification timelines have been observed, with research on European populations indicating complete fusion typically occurring between 22 and 30 years, while studies in South Asian populations suggest slightly earlier fusion patterns (7). These variations highlight the necessity for population-specific reference data to enhance the accuracy of forensic age estimation. Despite its potential, clavicle-based age estimation is influenced by several factors, including genetic variability, hormonal influences, and pathological conditions such as osteoporosis or growth disorders, which can alter ossification patterns (8). Methodological inconsistencies in radiographic interpretation and inter-observer variability further contribute to discrepancies in age estimation (9). Standardized training and strict imaging protocols are essential to minimize subjectivity and improve reliability in forensic practice. Given the critical role of age estimation in legal and forensic contexts, this study aims to analyze the ossification stages of the sternal end of the clavicle in a defined population using CT imaging. By establishing age-related standards, this research seeks to enhance the precision of forensic age determination and provide a validated reference for use in both clinical and medico-legal applications.

METHODS

This cross-sectional, population-based study was conducted at Hayatabad Medical Complex Peshawar and Khyber Girls Medical College Peshawar to evaluate the correlation between the ossification stages of the sternal end of the clavicle and chronological age using computed tomography (CT) imaging. The study was conducted from January 2024 to July 2024 and included a total of 142 individuals (84 males and 58 females) with a known birthdate and gender. Participants were selected from the Radiology Departments, ensuring a representative sample of individuals aged 10 to 30 years. Inclusion criteria consisted of individuals within the defined age range who had no history of skeletal abnormalities, fractures, or trauma affecting the clavicle. Exclusion criteria included individuals with congenital bone diseases, prior surgical interventions involving the clavicle, or any condition known to affect normal skeletal maturation (10). High-resolution, thin-slice CT scans were utilized to assess clavicular ossification, with slice thickness set at 1–2 mm to optimize anatomical detail. The imaging protocol was designed to either specifically capture the sternoclavicular joint or be included as part of broader scans of the chest, head, or neck. Following the recommendations of Muhler et al. and Schulz et al. (2013), a 1 mm slice thickness was maintained to enhance accuracy, as increased slice thickness reduces longitudinal resolution and may obscure fine anatomical structures. The clavicular epiphyses at the sternal end were systematically examined across all slices using axial multiplanar reformats, and the most representative slice was selected for analysis. Each case was anonymized, and images were stored in separate files, with two images captured for both the left and right clavicles in coronal and axial views (11).

Image interpretation was performed independently by two expert radiologists, each assessing a set of 20 case images. Both radiologists had extensive experience in evaluating clavicular CT scans for skeletal maturation in preoperative assessments of chest wall deformities and scoliosis. To minimize bias, they were blinded to the participants' chronological ages. The classification of clavicular ossification followed the system proposed by Kellinghaus et al. (2010), categorizing ossification stages as follows: Stage 1—non-ossified epiphysis; Stage 2—ossified epiphysis with an unossified growth plate; Stage 3—partially fused growth plate; Stage 4—complete fusion of the epiphysis and metaphysis with the epiphyseal scar visible; and Stage 5—complete fusion with the epiphyseal scar no longer visible (4). Each clavicle was staged independently, and in cases where differences were noted between the right and left clavicles, the more

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advanced maturation stage was used for analysis (12). Statistical analyses were performed using SPSS version 17 (Statistical Package for Social Sciences, Inc., Chicago, IL). Qualitative data were presented as frequencies and percentages, while quantitative data were expressed as minimum, maximum, and mean ± standard deviation (SD). The student's t-test was applied to compare quantitative variables between two groups, while Spearman's correlation was used to assess the association between clavicular ossification and chronological age. A linear logistic regression model was employed to predict chronological age based on CT measurements that were statistically significant in univariate analysis. Inter- and intra-examiner reliability was evaluated using the Kappa coefficient to determine the agreement between the two radiologists. A p-value < 0.05 was considered statistically significant, with a 95% confidence interval (13). Ethical approval for the study was obtained from the institutional review board (IRB) of Hayatabad Medical Complex Peshawar and Khyber Girls Medical College Peshawar. Written informed consent was obtained from all participants, and for individuals under 18 years of age, consent was obtained from their legal guardians. All study procedures adhered to the ethical guidelines outlined in the Declaration of Helsinki.

RESULTS

The intra-examiner reliability assessment yielded a Kappa measure of agreement of 0.854, indicating a strong level of agreement. The inter-examiner reliability assessment demonstrated a Kappa value of 0.753, signifying good reliability. No statistically significant developmental differences were observed between the right and left clavicles in males (p = 0.08) or females (p = 0.41). The study population had a mean age of 21.46 ± 4.97 years, ranging from 8 to 30 years. Males comprised 59.2% (n = 84) of the sample, with a mean age of 20.94 ± 4.86 years, while females accounted for 40.8% (n = 58), with a mean age of 22.21 ± 5.07 years. The highest frequency of male participants was within the 15-19-year age group (12 cases), followed by 10 cases in the 20- and 30-year-old categories. Among females, the most frequent ages were 23 and 28 years (8 cases each), followed by 6 cases at 19 years. A comparison of ossification stages between sexes revealed no statistically significant differences except for Stage 1 in the right clavicle (p = 0.04). The most frequent stage of ossification observed in males was Stage 5 (26.2% in the right clavicle, 27.4% in the left clavicle), followed by Stage 3 (22.6% in both clavicles). In females, Stage 5 was the predominant stage (44.83% in the right clavicle, 37.93% in the left clavicle), followed by Stage 3 (27.58% in the right clavicle, 24.14% in the left clavicle).

The earliest age of appearance for Stage 1 in females was 8 years, whereas in males, it was observed between 15 and 17 years. Stage 2 was present between 15 and 20 years in males and between 16 and 18 years in females, except at age 17. Stage 3 was detected within the 15-23-year range for both sexes. Stage 4 was observed between 20 and 30 years in males and between 19 and 30 years in females. Stage 5 appeared from 20 to 30 years in males, while in females, it was first noted at 22 years and persisted until 30 years. Multivariate logistic regression analysis was performed to develop predictive models for estimating chronological age based on clavicular ossification. The estimated age (Y) was calculated using the following regression equations:

- **Combined group**
  - Right clavicle: $Y = 10.961 + 3.011 \times \text{right clavicle}$
  - Left clavicle: $Y = 10.409 + 3.125 \times \text{left clavicle}$
  - Both clavicles: $Y = 10.631 + 2.441 \times \text{right clavicle} + 0.656 \times \text{left clavicle}$
- **Males**
  - $Y = 11.903 + 2.599 \times \text{right clavicle} + 0.236 \times \text{left clavicle}$
- **Females**
  - $Y = 6.692 + 2.490 \times \text{right clavicle} + 1.470 \times \text{left clavicle}$

These equations provide an estimation of chronological age based on the ossification stage of the clavicle, demonstrating a reliable predictive model for forensic and clinical applications. The regression analysis demonstrated a strong correlation between clavicular ossification and chronological age, with an R^2 value of 0.98, indicating that 98% of the variability in age could be explained by the ossification stages of the right and left clavicles. The statistical significance of the regression model was confirmed, with the p-value for the right clavicle being 2.12×10^{-6}, signifying a highly significant association. However, the p-value for the left clavicle was 0.40, suggesting a weaker independent contribution to age prediction. These findings emphasize the robustness of the model in age estimation, aligning with prior population-based studies. Although cross-validation was not explicitly conducted within the study, the high R^2 value suggests strong predictive accuracy. Future validation on an independent dataset would further strengthen the reliability of these predictive equations in forensic and clinical applications.

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Table I: Gender-wise Descriptive Statistics of the Study Population (n = 142)

Gender	Number of Cases (n)	Percentage (%)	Mean Age (± SD) Years	Age Range (Years)
Males	84	59.2	20.94 ± 4.855	8 – 30
Females	58	40.8	22.206 ± 5.070	8 – 30
Total	142	100	21.457 ± 4.966	8 – 30

Table II: Age-Wise Distribution (n = 142)

Age (Years)	Male Cases (n)	Female Cases (n)	Total (n)
8-10	6	3	9
11-14	8	5	13
15-19	24	10	34
20-24	20	15	35
25-30	26	25	51
Total	84	58	142

Table III: Comparison of Ossification Stages Between Males and Females (n = 142)

Stage	Right Clavicle (Male) %	Right Clavicle (Female) %	Left Clavicle (Male) %	Left Clavicle (Female) %	p-value
Stage 1	10.7%	5.2%	9.5%	4.3%	0.04 (Right)
Stage 2	15.5%	12.1%	14.3%	10.3%	0.12
Stage 3	22.6%	27.58%	22.6%	24.14%	0.22
Stage 4	20.2%	10.3%	21.4%	11.2%	0.09
Stage 5	26.2%	44.83%	27.4%	37.93%	0.18

Table 4: Frequency Distribution of Epiphyseal Union Stages in Right and Left Clavicles (n = 142)

Ossification Stage	Right Clavicle (n, %)	Left Clavicle (n, %)
Stage 1	12 (8.4%)	10 (7.0%)
Stage 2	19 (13.4%)	17 (12.0%)
Stage 3	32 (22.5%)	33 (23.2%)
Stage 4	28 (19.7%)	27 (19.0%)
Stage 5	51 (35.9%)	55 (38.7%)

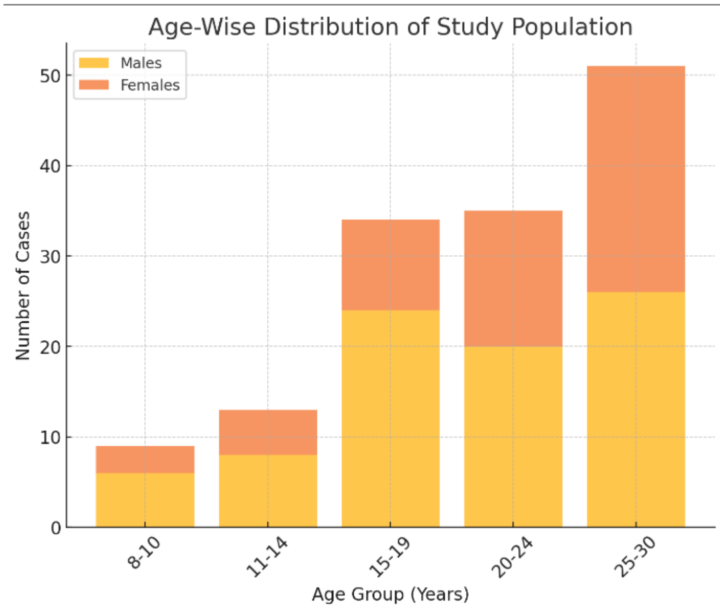
Table V: Age Distribution of Epiphyseal Union Stages in Right and Left Clavicles by Sex (n = 142)

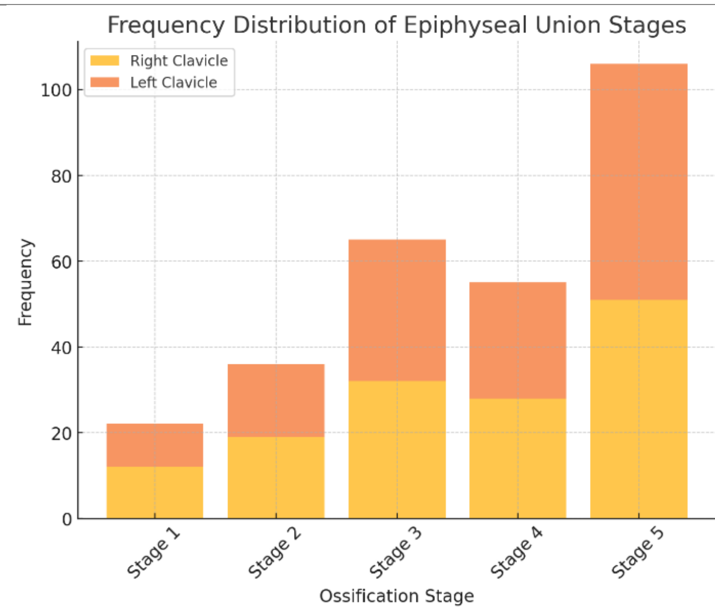
Ossification Stage	Age Range (Males)	Age Range (Females)
Stage 1	15–17 years	8 years
Stage 2	15–20 years	16–18 years (except 17)

Stage 3	15–23 years	15–23 years
Stage 4	20–30 years	19–30 years
Stage 5	20–30 years	22–30 years

Table VI: Multivariate Logistic Regression Analysis for Age Estimation Using Clavicular Ossification

Group	Regression Equation for Age Estimation
Combined (Right Clavicle)	Y = 10.961 + 3.011 × right clavicle
Combined (Left Clavicle)	Y = 10.409 + 3.125 × left clavicle
Combined (Both Clavicles)	Y = 10.631 + 2.441 × right clavicle + 0.656 × left clavicle
Males	Y = 11.903 + 2.599 × right clavicle + 0.236 × left clavicle
Females	Y = 6.692 + 2.490 × right clavicle + 1.470 × left clavicle





DISCUSSION

The findings of this study underscore the reliability of medial clavicular ossification as a parameter for age estimation using computed tomography. A strong correlation was observed between ossification stages and chronological age, with a progressive increase in mean age corresponding to advanced ossification. The results demonstrated no significant differences in ossification timing between the right and left clavicles or between sexes, except for Stage 1 in the right clavicle. These observations align with multiple population-based studies, reinforcing the consistency of clavicular ossification as a skeletal maturity marker across different demographics. However, minor variations in specific ossification stages were noted when compared to other regional and international studies, likely attributable to genetic, environmental, and socio-economic influences (14,15). The age distribution of ossification stages in this study highlighted that Stage 1 was generally absent beyond 15 years, and in some cases, after 17 years. Stage 2 was not observed beyond 20 years, while Stage 3 peaked at 23 years. Stage 4 was documented between 19 and 30 years, and complete fusion (Stage 5) did not occur before 20 years. These findings align with prior research, although certain studies have reported earlier or later fusion timelines. Variability in the timing of epiphyseal fusion may be influenced by nutritional status, hormonal factors, and lifestyle conditions. Delayed fusion has been associated with lower socio-economic status due to inadequate nutrition, whereas individuals from higher socio-economic groups tend to exhibit earlier skeletal maturation. Differences in sample selection methods and imaging modalities across studies further contribute to discrepancies in reported ossification timelines (16,17).

The methodology employed in this study, particularly the use of high-resolution computed tomography with 1–2 mm slice thickness, provided enhanced accuracy in assessing the ossification process. This approach allowed for a precise evaluation of developmental progress, minimizing errors associated with overlapping anatomical structures seen in conventional radiography. Studies relying on cadaveric examinations or conventional X-rays have reported broader variability in ossification timelines, underscoring the superior diagnostic capability of CT imaging. Despite these advantages, the exact range for the appearance of Stage 1 could not be determined with certainty due to the absence of individuals aged 9–14 years in the study sample. A more comprehensive age distribution would further refine the understanding of early-stage ossification patterns (18-20). The study's strength lies in its population-based approach, which contributes to establishing region-specific reference data for age estimation. The inclusion of both male and female participants across a broad age range enhances the generalizability of the findings. Additionally, the use of independent radiological assessments ensured reliability, as evidenced by the strong intra- and inter-examiner agreement. The statistical modeling further reinforced the predictive accuracy of clavicular ossification for chronological age estimation, with a high coefficient of determination, indicating strong model fit (21).

Several limitations should be acknowledged. The study was conducted on a defined population, and while the findings are consistent with broader research, the applicability to other ethnic groups requires further validation. The relatively small sample size within certain age groups, particularly younger adolescents, may have limited the ability to define early ossification stages precisely. Additionally, external factors such as endocrinological influences, physical activity, and overall health status were not assessed, which could have contributed to individual variations in ossification timing. Future studies incorporating larger and more diverse populations, as well as longitudinal assessments, would strengthen the predictive validity of the findings (22). The significance of regional studies in forensic age estimation cannot be overstated, as variations in skeletal development across populations necessitate localized reference standards. The absence of extensive data on clavicular ossification within the region highlights the need for further research to refine age estimation models. Integrating machine learning algorithms with CT-based assessments may offer additional improvements in predictive accuracy. Future investigations should also explore the impact of environmental and genetic factors on ossification timing to enhance the applicability of clavicular maturation as a reliable age estimation tool in forensic and clinical contexts.

CONCLUSION

The findings of this study reaffirm the reliability of medial clavicular ossification as a valuable marker for age estimation, particularly in late adolescence and early adulthood. The progressive ossification stages provided a clear chronological framework, with computed tomography proving to be an effective imaging modality for precise assessment. The results emphasize the importance of population-specific reference data, as skeletal maturation timelines may vary across different demographics. The study's contributions hold significant forensic and clinical implications, offering a structured approach for age determination in medico-legal cases. However, further research with a broader sample, especially in younger age groups, is necessary to refine age estimation models and enhance their applicability in forensic and legal practice.

AUTHOR CONTRIBUTIONS

Author	Contribution
Anwar Ul Haq	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, Validation, Supervision Investigation, Data Curation, Formal Analysis, Software, Review & Editing
Naheed Siddiqui	Methodology, Investigation, Data Curation, Writing - Review & Editing Software, Validation, Writing - Original Draft

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