

Comparison of imaging planes during CT-based evaluation of clavicular ossification: a multi-center study

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Abstract Determining the ossification stage of the medial clavicular epiphysis by computed tomography represents the currently recommended methodology for the question of whether a living individual has completed the 18th or 21st year of life. In the present study, thin-slice CT scans of 1078 sternoclavicular joints were reconstructed in axial and coronal image series and evaluated according to the two classification systems established for age diagnostics using the clavicle. Both image series (axial and coronal) were analyzed separately. When comparing the results of axial and coronal view, a different ossification stage was found in 35.6% of the clavicles. The results suggest an influence of the imaging plane on the process of stage determination. In order to further approximate the three-dimensional and asymmetrical structure of the epiphyseal ossification center, the usage of at least two

different reformation types may be recommended. In practice, only those reference studies should be applied which exactly employed the same number and orientations of the reformation types that are going to be used in the respective routine case.

Keywords Forensic age diagnostics · Medial clavicular epiphysis · Ossification stage · Computed tomography · Imaging plane

Abbreviations

MCE Medial clavicular epiphysis
CT Computed tomography
AX Axial image series
COR Coronal image series
MPR Multi planar reformation

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Introduction

During recent years, the investigation of the medial clavicular epiphysis (MCE) has been established as the most reasonable approach to answer the question raised by different authorities whether an individual without known chronological age has completed the age of 18 or 21 years [1, 2]. Other maturation indicators, such as the bones of the hand/wrist region, the iliac crest apophysis, or the third molars were repeatedly shown to be unsuitable concerning this question because their development may be completed before achieving the age of majority (18 years in many European countries) [3–10].

Following the current recommendations of the Study Group on Forensic Age Diagnostics (AGFAD) of the German Society of Legal Medicine, the developmental status of the MCE should be evaluated either by projection

radiography (PR) or computed tomography (CT) [11]. However, according to recent results, CT should be given preference, if the procedure of age estimation can be planned in advance and a CT scanner is even available [12, 13]. The prerequisites for this approach are both a legal basis for exposure to radiation and the proof of complete ossification of the hand/wrist region [2, 11].

The determination of the MCE's ossification stage by means of CT is known to be influenced by different factors, such as the slice thickness [14] or the qualification of the examiner [15]. During daily casework, we also observed different geometrical orientations of the epiphyseal ossification center of the MCE suggesting that the reformation type, i.e., the type of the imaging plane used for evaluation (axial, coronal, or other types), might be another influencing factor. When analyzing CT studies of the last 20 years dealing with the investigation of the MCE for age estimation purposes, it becomes apparent that different and heterogeneous algorithms of reformations were chosen, such as axial only [14, 16–20] or axial in conjunction with other reformation types [15, 21–35].

Therefore, we were interested in the question of whether a change of the view may possibly lead to a change of the stage diagnosis as well. Accordingly, the present study aimed on the investigation of the influence of the reformation type on the stage determination of the MCE.

Materials and methods

Specimens

During forensic autopsies of 572 bodies aged between 10 and 40 years, the sternoclavicular joints were prospectively collected at 5 university institutes of legal medicine (Hamburg, Essen, Frankfurt/Main, Berlin, and Münster). If the autopsy had revealed a growth disorder or any other disease affecting skeletal development, the case was primarily not included in the study. After removal from the body, the specimens were immediately deep-frozen at $-20\text{ }^{\circ}\text{C}$ and subsequently transported to the Institute of Legal Medicine in Münster. For a better handling and long-term conservation, the specimens were shrink-wrapped, i.e., packaged by enclosing it in clinging transparent plastic film that shrinks tightly on to it. Storage and transportation was continuously done at $-20\text{ }^{\circ}\text{C}$.

Thirty-three cases had to be excluded due to incomplete information. In total, 539 cases (1078 sternoclavicular joints) were available for assessment. Ethical approval was obtained from all local ethics boards of the participating institutions.

Subsequently, each specimen was scanned using a 40-row multi-detector computed tomography (MDCT) system (SOMATOM Sensation 40, Siemens, Erlangen, Germany; FOV 200×200 , matrix 512×512 , pixel spacing 0.39×0.39 , 120 kV, 90 mA, kernel B70s, slice thickness

0.6 mm). Using a standard picture archiving and communications systems (PACS) workstation, the resulting image material was viewed by means of two different reformation types:

1. Axial image series (AX) = transverse sections
2. Coronal image series (COR) = frontal sections

Stage determinations

The degree of the ossification of each MCE ($n = 1078$) was separately determined applying both the five-stage classification system by Schmeling et al. [36] and the classification system by Kellinghaus et al. [22] sub-dividing the main stages 2 and 3 into the sub-stages 2a, 2b, 2c, 3a, 3b, and 3c. Stage determinations were done according to the procedures described recently [37]. Schematic drawings of all stages and further details on the classification systems are shown in Fig. 1. MCEs which could not be assigned to one of the aforementioned stages were classified as “not assessable” (n.a.). Both image series (AX and COR) were analyzed separately with an interval of 4 weeks.

Two examiners did the stage determinations in consensus. Both examiners have several years of experience in evaluating

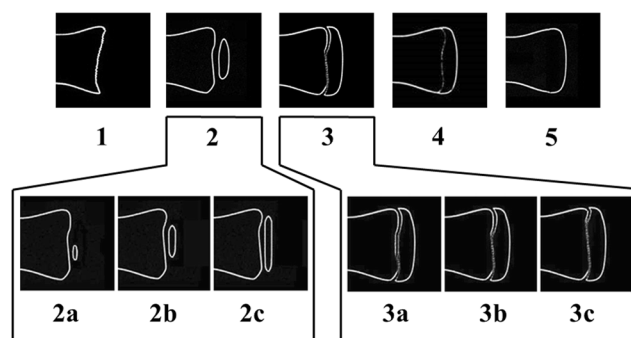


Fig. 1 Stage determination of the medial clavicular epiphysis. The *upper row* shows the classification system by Schmeling et al. [36]. Stage 1 = ossification center not ossified. Stage 2 = ossification center ossified. Epiphyseal cartilage not ossified. Stage 3 = epiphyseal cartilage partially ossified. Stage 4 = epiphyseal cartilage completely ossified. Epiphyseal scar is visible. Stage 5 = epiphyseal cartilage completely ossified. Epiphyseal scar is not visible anymore. The *lower row* shows the amplified sub-staging scheme by Kellinghaus et al. [22] Stage 2a = the lengthwise epiphyseal measurement is one third or less compared to the widthwise measurement of the metaphyseal ending. Stage 2b = the lengthwise epiphyseal measurement is over one third to two thirds compared to the widthwise measurement of the metaphyseal ending. Stage 2c = the lengthwise epiphyseal measurement is over two thirds compared to the widthwise measurement of the metaphyseal ending. Stage 3a = the epiphyseal-metaphyseal fusion completes one third or less of the former gap between epiphysis and metaphysis. Stage 3b = the epiphyseal-metaphyseal fusion completes over one third to two thirds of the former gap between epiphysis and metaphysis. Stage 3c = the epiphyseal-metaphyseal fusion completes over two thirds of the former gap between epiphysis and metaphysis

CT images of the MCE. Prior to and during the image evaluations, the examiners did not have access to the individuals' meta data to avoid any influence from age or sex.

Merging of ossification stages

In order to merge the information of AX and COR into a single and final ossification stage for each clavicle, the rules that have been developed recently for the combination of multiple CT slices [37] were used:

1. If a medial clavicular epiphysis shows features of stages 1 and 2, or features of stages 2 and 3, the higher stage must be assigned (1 + 2 → 2, 2 + 3 → 3).
2. If a medial clavicular epiphysis shows features of stages 3 and 4, or features of stages 4 and 5, the lower stage must be assigned (3 + 4 → 3, 4 + 5 → 4).

In addition, these rules were expanded on sub-stages. Table 1 provides an overview of the resulting combinations of ossification stages encountered during separate stage determinations in AX and COR.

Results

A comparison of the ossification stages between the assessments of AX and COR is summarized in Table 2.

The fields highlighted in *green* show the number of MCEs in which the same ossification stage was assigned in both AX and COR ($n = 694$ out of 1078, 64.4% of the MCEs); for example, 26 MCEs revealed a stage 3a in both the axial and the coronal depiction of the same MCE.

The fields highlighted in *yellow* show the number of MCEs in which a different ossification stage was found in COR compared to AX ($n = 384$ out of 1078, 35.6% of the MCEs). These fields can further be sub-divided into four different groups:

- #1) The fields framed in *orange* reveal the number of MCEs ($n = 28$, 2.6%) in which, firstly, a higher ossification stage was found in COR compared to AX, and secondly, when combining the information from AX and COR, the ossification stage determined in COR is decisive for the final stage assignment (Fig. 2).

Table 1 Combination of ossification stages determined separately in axial and coronal view. Fields with “x” represent combinations that did not occur in our study

CLAVICULAR OSSIFICATION STAGE		CORONAL VIEW									
		1	2a	2b	2c	3a	3b	3c	4	5	n.a.
AXIAL VIEW	1	1	2a	x	x	x	x	x	x	x	n.a.
	2a	x	2a	2b	x	x	x	x	x	x	n.a.
	2b	x	2b	2b	x	3a	x	x	x	x	n.a.
	2c	x	2c	2c	2c	x	x	x	x	x	n.a.
	3a	x	3a	3a	3a	3a	3b	x	x	x	n.a.
	3b	x	x	x	x	3b	3b	3c	x	x	n.a.
	3c	x	x	x	x	x	3c	3c	3c	x	n.a.
	4	x	x	x	x	x	x	3c	4	4	n.a.
	5	x	x	x	x	x	x	x	4	5	n.a.
	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 2 Comparison between axial and coronal view. The numbers indicate number of MCEs. Colors are explained in detail within the “Results” section

Clavicular ossification stage		Coronal view									
		1	2a	2b	2c	3a	3b	3c	4	5	n.a.
Axial view	1	21	1	0	0	0	0	0	0	0	2
	2a	0	7	4	0	0	0	0	0	0	2
	2b	0	7	3	0	4	0	0	0	0	1
	2c	0	1	2	0	0	0	0	0	0	1
	3a	0	1	2	1	26	7	0	0	0	1
	3b	0	0	0	0	10	15	12	0	0	5
	3c	0	0	0	0	0	4	63	9	0	3
	4	0	0	0	0	0	0	12	219	15	20
	5	0	0	0	0	0	0	0	26	56	1
	n.a.	8	7	2	0	27	18	49	101	18	284

#2) The fields framed in *purple* show the number of MCEs ($n = 24, 2.2\%$) in which, firstly, a higher ossification stage was found in COR compared to AX, and secondly,

the ossification stage determined in AX is decisive for the final stage assignment when combining the information from AX and COR.

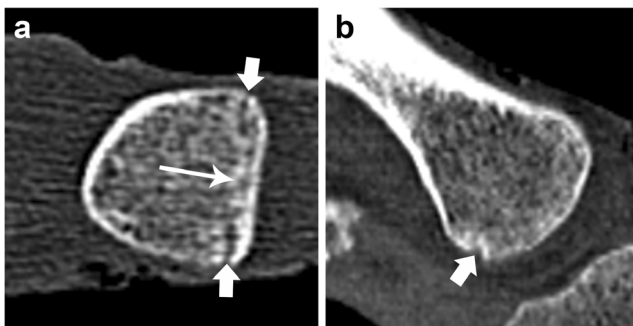


Fig. 2 In this case example, the axial view (a) shows an incompletely ossified MCE consistent with an ossification stage 3b. The *thick arrows* point at the “open” (unfused) parts of the cartilaginous growth plate. The *thin arrow* points at the epiphyseal scar which can already be seen within the ossification zone but has no relevance for the ossification stage. In the coronal view (b), the same MCE has been evaluated independently as stage 3c because of the advanced ossification status between metaphysis and epiphyseal ossification center. The *thick arrow* points at the “open” (unfused) part of the cartilaginous growth plate

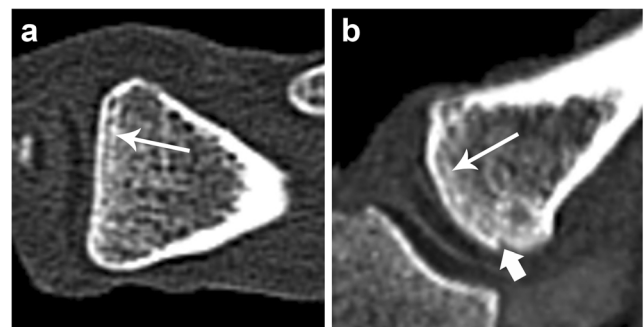


Fig. 3 In this case example, the axial view (a) shows a completely ossified MCE with the presence of an epiphyseal scar (*thin arrow*) consistent with an ossification stage 4. In the coronal view (b), the same MCE has been evaluated independently as stage 3c because, besides the presence of an epiphyseal scar (*thin arrow*), the MCE still reveals “open” (unfused) parts of the cartilaginous growth plate (*thick arrow*)

- #3) The fields framed in *blue* represent the number of MCEs ($n = 28$, 2.6%) in which, firstly, a lower ossification stage was observed in COR compared to AX, and secondly, the ossification stage determined in AX is decisive for the final stage assignment when combining the information from AX and COR.
- #4) The fields framed in *red* demonstrate the number of MCEs ($n = 38$, 3.5%) in which, firstly, a lower ossification stage was found in COR compared to AX, and secondly, the ossification stage determined in COR is decisive for the final stage assignment when combining the information from AX and COR (Fig. 3).

Discussion

The aim of this prospective study was to investigate the relevance of the imaging plane for the evaluation of clavicular ossification using computed tomography. To this end, 1078 sternoclavicular joints obtained during forensic autopsies were scanned and separately analyzed by means of two different reformation types, the axial and the coronal view.

When analyzing Table 2, a relatively high number of cases that are finally evaluated as “not assessable” (n.a.) may attract attention. This phenomenon may be attributed to the study design. According to Table 1, which is based on the merging rules described previously [37], all cases that presented with an anatomical shape variant in one orientation only were finally classified as “not assessable.”

Comparison of the results determined in AX and COR revealed consistent ossification stages in 64.4% and different ossification stages in 35.6% of the MCEs. The latter can further be sub-divided into four relevant groups.

As to the group #1 (orange-framed fields in Table 2), where the ossification stage determined in COR is higher than in AX and yet decisive for the final stage assignment, it must be realized that additional consideration of the COR information results in a higher final ossification stage instead of considering the AX information only.

The situation is different with regard to the group #2 (purple-framed fields in Table 2) where the ossification stage determined in AX is decisive for the final stage assignment, although the ossification stage determined in COR is higher. Hence, both the sole consideration of the AX information and the combined consideration of AX + COR lead to the same final ossification stage.

Group #3 (blue-framed fields in Table 2) is the group in which the ossification stage determined in COR is lower than in AX and AX is decisive for the final stage assignment. As with group #2, both the sole consideration of the AX information and the additional consideration of the COR information lead to the same final ossification stage.

Group #4 (red-framed fields in Table 2) consists of MCEs in which the ossification stage determined in COR is lower than in AX and yet decisive for the final stage assignment. Combined consideration of the AX + COR information results in a lower final ossification stage, compared to the sole consideration of the AX information.

The reasons for the different stage diagnoses found in this study are manifold. Different sub-stages, for example stage 3a in AX and stage 3b in COR, may clearly be explained by an asymmetric geometry of the epiphyseal ossification center which is known to be flake-like in many cases and not perfectly circular. Differences as to stage 3 and 4 may be attributed to wedge-like remnants of the epiphyseal cartilage (so-called “open growth plates”) that may obviously be visible in one orientation only. This is possible because only the first or last slice of a reformation type may contain this wedge-like remnant and may therefore lead to another stage diagnosis (Fig. 3). Our study also revealed MCEs in which the epiphyseal scar in a completely fused MCE could only be seen in one orientation but not in the other one resulting in stage 5 instead of stage 4 and vice versa. This phenomenon may be due to the orientation of epiphyseal scar remnants that may appear as short distance densities on single slices of the first reformation type but only dot-like in the second one; thereby, the physcal scar may be unrecognizable in comparison with surrounding cancellous bone.

For the investigation and assessment of the epiphyseal ossification center of the MCE, some authors currently use distance measurements within the axial plane only. However, this approach has to be regarded as sub-optimal since those measurements are not able to reflect the three-dimensional and asymmetrical geometry of the epiphyseal ossification center truthfully and sufficiently. Hence, the consideration of an additional image plane (e.g., COR) constitutes an improvement by providing an additional perspective with additional information on the three-dimensional object of investigation.

Another approach was presented by Wei et al. [38]. The authors used three-dimensional CT volume rendering (VR) images of the medial clavicle in 795 adolescent subjects to measure ratios between the longest epiphyseal and metaphyseal diameters as well as between epiphyseal and metaphyseal areas. The correlation of these two ratios with the subject’s chronological ages revealed R^2 values above 0.603. In addition, the study also demonstrated an asymmetrical and often elliptical geometry of the MCE which are in line with observations of the present study. As to the sub-stages 3a–c, it would be interesting to quantify the fusion areas between epiphyseal ossification center and the metaphyseal plate using the three-dimensional approach. However, the major problem has probably to be seen in the adjustment of the correct image plane that should exactly be located between the epiphyseal ossification center and the medial metaphyseal plane.

The influence of the image plane and the geometry of the epiphyseal ossification center might become relevant not only for CT studies but also for study approaches investigating the possibilities of magnetic resonance imaging (MRI) for the evaluation of clavicular ossification. So far, only relatively few studies have shed some light on MRI of the MCE for age estimation purposes [39–46]. However, comprehensive reference data may be expected in near future [47].

Conclusions

The present pilot study has been the first to determine clavicular ossification stages in AX and COR separately. The results suggest an influence of the imaging plane on the process of stage determination that should further be investigated in larger case cohorts. In order to further approximate the three-dimensional and asymmetrical structure of the epiphyseal ossification center, the usage of at least two different reformation types providing two different views on the study object may be recommended for the evaluation of the MCE by means of computed tomography. In forensic age estimation practice, only those reference studies should be applied which exactly employed the same number and orientations of the reformation types that are going to be used in the respective routine case.

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