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REVIEW

Systematic procedure for identifying the five main ossification stages of the medial clavicular epiphysis using computed tomography: a practical proposal for forensic age diagnostics

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Abstract In forensic age estimations of living individuals, computed tomography of the clavicle is widely used for determining the age of majority. To this end, the degree of ossification of the medial clavicular epiphysis can be determined by means of two classification systems complementing each other: a 5-stage system and an additional 6-stage system that further sub-classifies the stages 2 and 3. In recent years, practical experience and new data revealed that difficulties and even wrong stage determinations may occur especially when following the short descriptions of the fundamental 5-stage system only. Based on current literature, this article provides a systematic procedure for identifying the five main ossification stages by listing important preconditions and presenting an algorithm that is comprised of four specific questions. Each question is accompanied by comprehensive and detailed descriptions which specify the criteria used for differentiation. The information is subdivided into "single-slice view" and "multi-slice view." In addition, illustrative case examples and schematic drawings facilitate application of the procedure in forensic practice. The pitfalls associated with the criteria of stage determination will be discussed in detail. Eventually, two general rules will be inferred to assign correct ossification stages of the medial clavicular epiphysis by means of computed tomography.

Keywords Forensic age diagnostics · Age estimation · Clavicle · Medial clavicular epiphysis · Ossification stages · Computed tomography

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Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
SSV	Single-slice view
MSV	Multi-slice view
EOC	Epiphyseal ossification center

Introduction

The whole Western world and the European Union in particular are faced with increasing levels of migration which occur mainly due to massive movement of refugees. This development leads to an increase of legal proceedings concerning individuals who are not able to prove their chronological age by valid identification documents. However, numerous legal decisions depend on those chronological ages. If authorities and courts do not succeed in dispelling doubts on a chronological age that was conveyed by a person without documents, medical experts may be requested to perform forensic age diagnostics.

The present situation of forensic age diagnostics in living individuals with special attention to methodological and legal aspects has recently been summarized by Schmeling et al. [1]. From a legal point of view, two different approaches can be distinguished:

If there is a legal basis for exposure to radiation without medical indication, the Study Group on Forensic Age Diagnostics (AGFAD) of the German Society of Legal Medicine (DGRM) currently recommends a physical examination combined with an evaluation of a hand/wrist radiograph plus a dental examination including the evaluation of an orthopantomogram [2]. However, the development of teeth and hand [3–6] as well as many other

maturation indicators of the human skeleton [7, 8] may already be completed before the age of 18 years which represents an important legal age threshold in many European countries. Accordingly, if the skeletal development of the hand/wrist region is already complete, the AGFAD recommends an additional radiological evaluation of the medial clavicular epiphysis using projection radiography (PR) or computed tomography (CT) [2]. If CT is available, then this modality should be given preference over PR [9].

If there is no legal basis for X-ray examinations, the AGFAD recommends a physical examination plus a dental examination [10]. Due to promising research results using X-ray-free imaging modalities, i.e., sonography [11, 12] and magnetic resonance imaging (MRI) [13–18], an increase of the validity of those forensic age estimations can be expected in the near future.

As mentioned above, the clavicle plays a crucial role in forensic age diagnostics, especially in terms of determining the age of majority [19]. In order to assess the degree of ossification of the medial clavicular epiphysis by means of CT, two important classification systems have been established during the last years, complementing each other:

(1.) The 5-stage classification system by Schmeling et al. [20] (Table 1) which was first introduced in a PR study and aims at transferring the traditional classification system known from osteology (stages 1 to 4) into a modified classification system which can directly be applied in forensic radiology and imaging. In addition, the imaging perspective allows for the discrimination of another ossification stage by detecting the complete absence of a physeal scar (stage 5).
(2.) The sub-classification system by Kellinghaus et al. [21] which sub-divides the main ossification stages 2 and 3 into the six sub-stages 2a, 2b, 2c and 3a, 3b, 3c, respectively.

The utility of these classification systems was repeatedly demonstrated not only by employing PR [22–24] and CT [25–31], but also by MRI pilot studies [13, 16, 32, 33]. However, practical experience and a recently published CT study [34] revealed that difficulties and even wrong stage determinations may occur when following the short descriptions of the fundamental 5-stage classification system only (Table 1). This applies, in particular to cross-sectional imaging that inherently involves a multislice view of the object examined. Errors made during the determination of the five main ossification stages may accordingly result in significant disadvantages for individuals subjected to age diagnostics.

Therefore, based on current literature, the present article aims to provide a clearly enunciated, practically oriented, and systematically structured procedure for the determination of correct clavicular ossification stages using the imaging modality of CT. To this end, seven important preconditions are introduced and followed by an algorithm comprising four specific questions (A–D) that eventually result in precise stage diagnoses. Each question has only two possible answers leading to a dichotomous overall structure. Furthermore, each question is accompanied by further descriptions and explanations which specify the criteria used for differentiation. The associated information is subdivided into two different views: “single-slice view” (SSV) and “multislice view” (MSV).

Preconditions

(1.) The CT scan must encompass the entire medial clavicular epiphysis of both clavicles. If the scan does not include, for instance, the peripheral parts of the epiphysis, a confident and unambiguous assignment to one of the ossification stages will not be possible.
(2.) The slice thickness should not exceed a maximum thickness of 1 mm in order to ensure maximum accuracy and diagnostic reliability. In 2006, Mühler et al. [35] were able to demonstrate that the stage diagnosis of a medial clavicular epiphysis may differ when using different slice thicknesses.
(3.) The image resolution must facilitate the detection of fine osseous structures.
(4.) Adequate image parameters must be chosen, i.e., CT images of the clavicle should be evaluated by using the “bone window view.”
(5.) Stage determinations should be done in consensus by at least two experienced examiners. The degree of specific qualification has been identified as crucial influence factor for the assessment of the medial clavicular epiphysis [34].
(6.) Each individual cross-sectional image of the respective medial clavicular epiphysis must be taken into account for determining the ossification stage of that epiphysis. A selection of single and supposedly representative slices is inadmissible and may result in wrong stage assessments.
(7.) Ossification stages must not be determined in clavicles where the medial clavicular epiphysis shows an anatomical shape variant such as bowl-like, or fish-mouth-like shapes, or multiple EOCs (Fig. 1). It is not yet known whether the shape variants are associated with the same correlations between developmental speed and morphological appearance.

Table 1 Short descriptions of the 5-stage classification system according to Schmeling et al. [20]

Ossification stage	Short description
1	The ossification center has not yet ossified.
2	The ossification center has ossified. The epiphyseal cartilage has not ossified.
3	The epiphyseal cartilage has partially ossified.
4	The epiphyseal cartilage has fused completely. The physeal scar is still visible.
5	The epiphyseal cartilage has fused completely. The physeal scar is not visible any more.

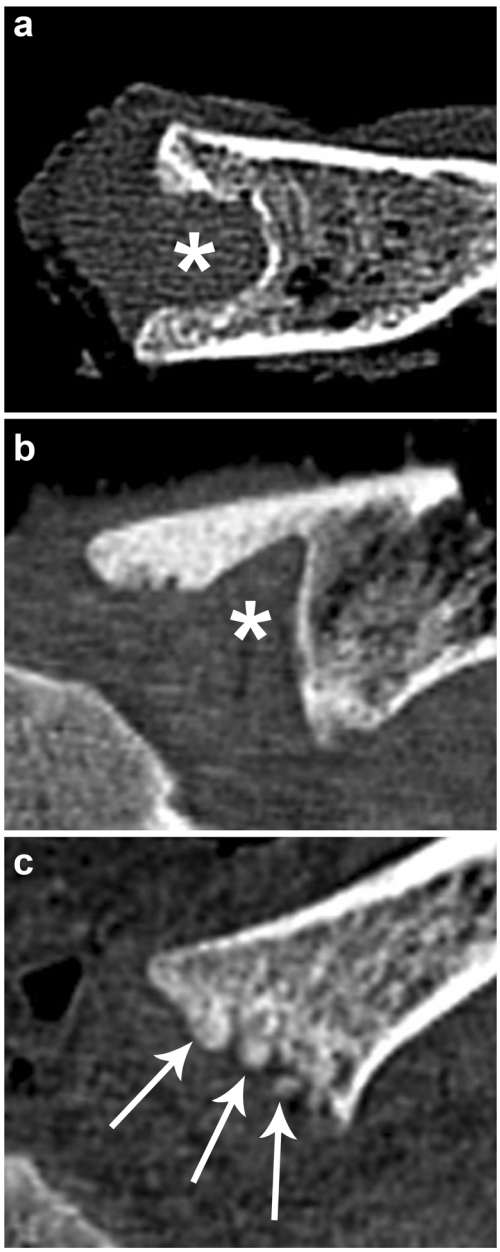

Fig. 1 Case examples of anatomical shape variants of the medial clavicular epiphysis. **a** Variant with a "bowl-like" depression (*asterisk*). **b** Variant with a "fish-mouth-like" depression (*asterisk*). **c** Multiple EOCs (*arrows*) that are not connected to each other, neither in this slice nor in the other slices. In this case, the two upper EOCs already have an osseous connection to the metaphysis

Algorithm for clavicular stage determination

Question A: Does the medial clavicle exhibit a separately definable epiphyseal ossification center that has either no or partial osseous connection to the metaphysis?

SSV: An "epiphyseal ossification center" (EOC) is a calcified area anywhere within the cartilage that primarily forms the medial epiphysis. The EOC may have an oval, rounded, or polygonal appearance. It may only be punctual or extend bar-like up to a total length corresponding to the maximum width of the adjacent metaphysis. Possible appearances of the EOC are summarized in Fig. 2. The EOC must not be confused with calcifications of adjacent connective or soft tissue belonging to, for instance, the articular disc, periarticular ligaments, or the articular capsule (Fig. 3).

MSV: In some cases, the EOC may be visible on one slice only.

- If the answer is YES, this may be a stage 2 or 3. Proceed with question B.
- If the answer is NO, this may be a stage 1, 4, or 5. Proceed with question C.

Question B: Is there an osseous connection (also be referred to as fusion area) between metaphysis and epiphyseal ossification center?

SSV: A "fusion area" is a calcified bridge-like connection anywhere between the osseous medial surface of the metaphysis and the EOC. The fusion area may appear singly, or fusion areas may be visible in groups. The fusion area may be developed focally or extend bar-like up to a total length that *nearly* corresponds to the maximum width of the adjacent metaphysis. Note that complete fusion between metaphysis and epiphysis has not been achieved, but remaining cartilaginous gaps of the physeal growth plate, which frequently occur wedge-shaped at the edges of the medial clavicular ending, are present. Fusion areas may already exhibit a so-called physeal scar, explained in more detail in question D. Note that, in contrast to question D, the physeal scar is not

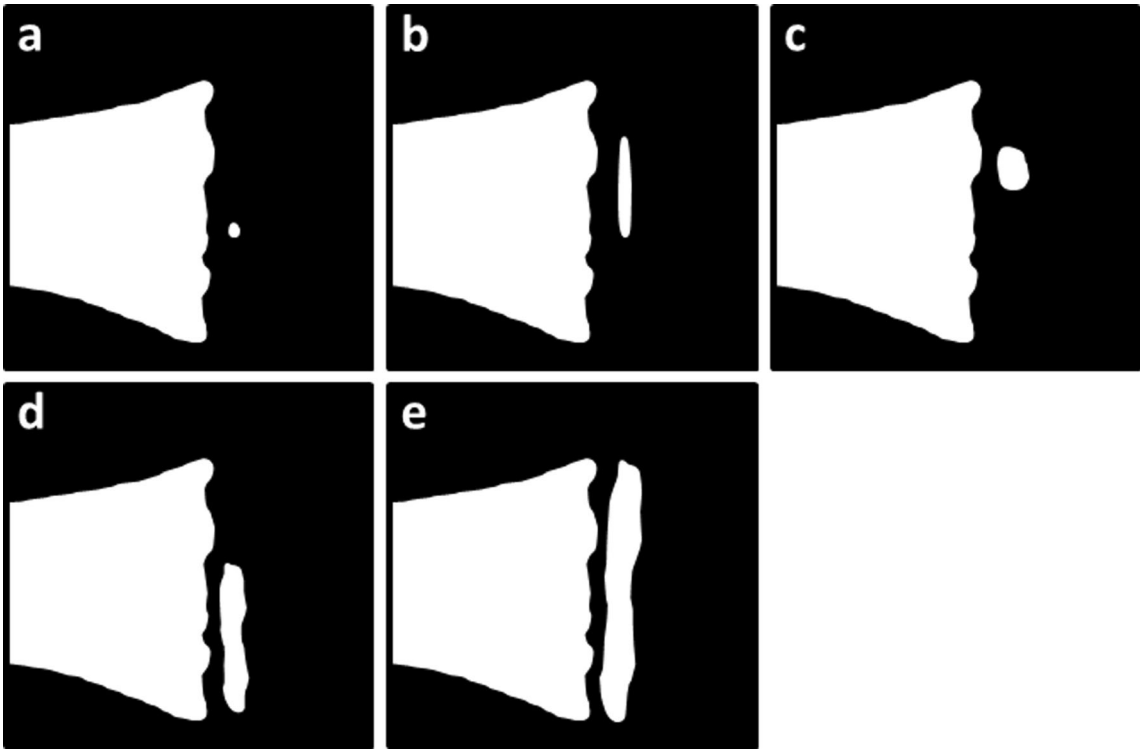

Fig. 2 Schematic drawings of possible appearances of the EOC. Note that this representative summary does not claim to be a complete presentation of all possibilities. **a** Small, slim, and punctual EOC. **b** Medium-sized, slim, and bar-like appearance of the EOC. **c** Wide, polygonal to rounded EOC. **d** Medium-sized, wide, and bar-like EOC. **e** EOC that extends bar-like up to a total length corresponding to the maximum width of the adjacent metaphysis

used as distinguishing criterion here because the ossification process has not been completed. Possible appearances of fusion areas are summarized in Fig. 4.

MSV: In some cases, fusion areas or remaining cartilaginous gaps may be recognizable on one slice only.

- If the answer is YES, this is a stage 3.
- If the answer is NO, this is a stage 2.

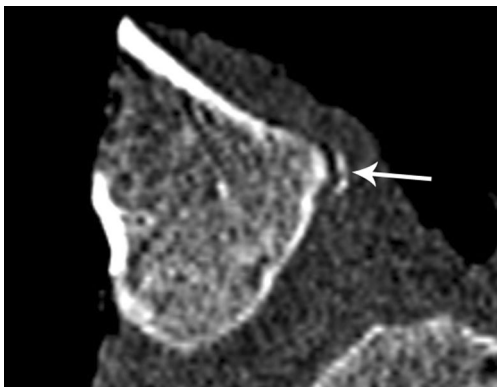

Fig. 3 Case example of a medial clavicular epiphysis revealing a calcification of adjacent connective tissue at the upper part of the epiphysis (*arrow*). This finding should not be confused with an EOC

Question C: Does the medial clavicular ending exhibit an irregular surface and/or edgy boundary lines?

SSV: An "irregular surface" is a bumpy, roughened, and non-linear surface that may look coral-like. It should not have a convex shape. "Edgy boundary lines" are acute-angled and do *not* appear smooth, curved, or rounded. The two opposing shapes, reflecting the earliest (no EOC) and the latest (complete fusion between EOC and metaphysis) appearances of the medial clavicular epiphysis, are shown in Fig. 5.

MSV: The features mentioned above will usually not appear on one slice only. Instead, a clear predominance of the configuration of the medial clavicular ending should be observable.

- If the answer is YES, this is a stage 1.
- If the answer is NO, this may be a stage 4 or 5. Proceed with question D.

Question D: Is there a physeal scar (also be referred to as epiphyseal scar)?

SSV: A "physeal scar" is a thin linear band of bone of higher density than the cancellous bone on either side. It is

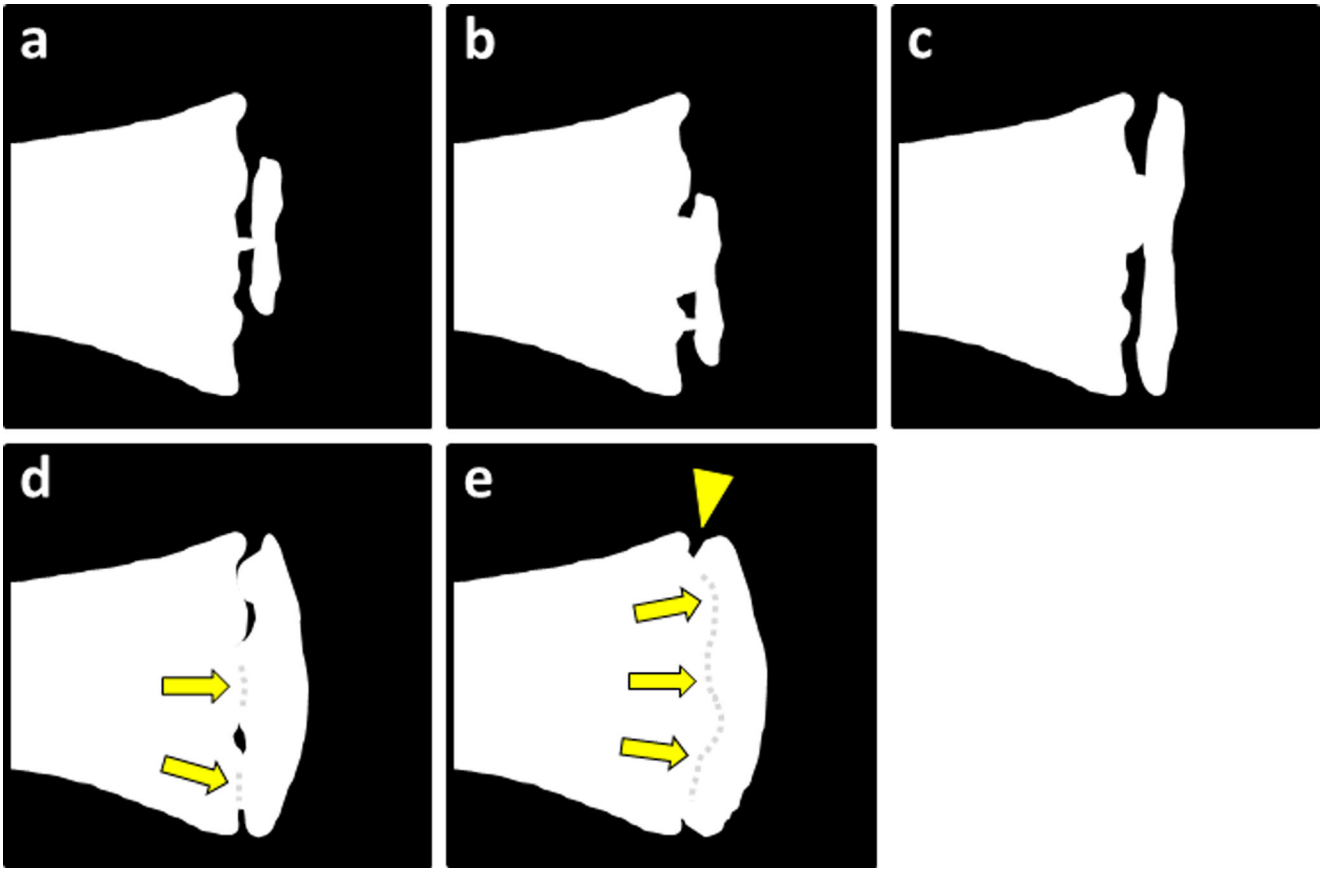

Fig. 4 Schematic drawings of possible appearances of fusion areas between EOC and metaphysis. Note that this representative summary does not claim to be a complete presentation of all possibilities. **a** Single punctual fusion area with EOC. **b** Multiple fusion areas of different sizes with EOC. **c** Single wide fusion area with an EOC. Note that, in this case, the EOC corresponds to the maximum width of the adjacent metaphysis. The presence of a stage 3 is, however, independent of the size of the EOC. **d** Multiple fusion areas with additional physeal scars (*yellow arrows*). **e** Single fusion area extending bar-like up to a total length nearly corresponding to the maximum width of the adjacent metaphysis. Note that the remaining wedge-shaped cartilaginous gaps at the edges (*yellow arrow head*). There may also be a physeal scar (*yellow arrows*) which is, however, not used as distinguishing criterion here as the ossification process has not been completed

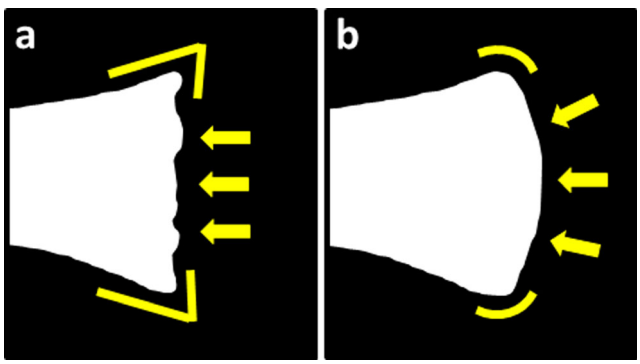

Fig. 5 Schematic drawings of the two opposing shapes that do not reveal a separately definable EOC. **a** Medial clavicular ending with irregular surface (*yellow arrows*) and edgy boundary lines (highlighted by *acute-angled yellow bars*). **b** Medial clavicular ending with a smooth and convex surface (*yellow arrows*) as well as smooth and rounded boundary lines (highlighted by *curved yellow bars*)

located at the position of the former growth plate between metaphysis and epiphysis. The physeal scar may extend up to a total length which corresponds to the maximum width of the adjacent metaphysis or it may be discontinuous, thus, presenting several interruptions. A physeal scar may also appear as single short remnant. Possible appearances of the physeal scar are summarized in Fig. 6.

MSV: The physeal scar should be considered present even if only remnants are recognizable on single slices. In some cases, the physeal scar may be visible on one slice only.

- If the answer is YES, this is a stage 4.
- If the answer is NO, this is a stage 5.

Discussion

In this article, we propose a systematic procedure for identifying the five main ossification stages of the medial clavicular

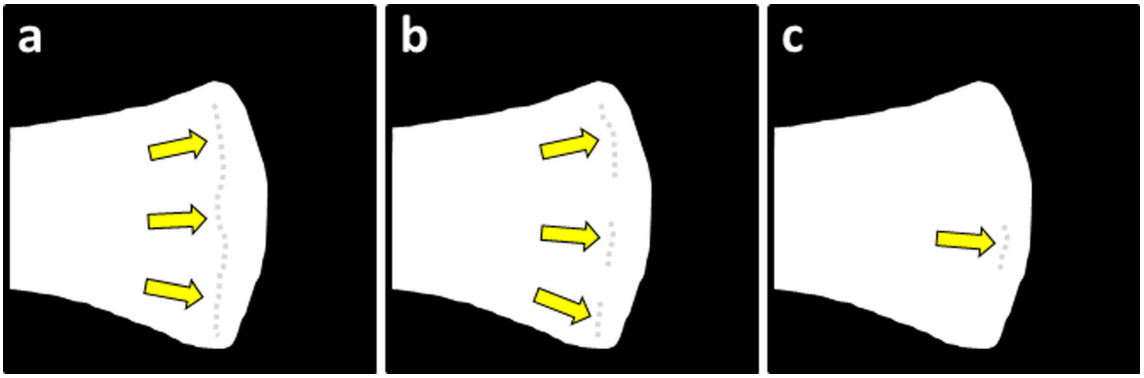

Fig. 6 Schematic drawings of possible appearances of the physeal scars (*yellow arrows*). **a** Physeal scar extending up to a total length corresponding to the maximum width of the metaphysis. **b** Physeal scar with several interruptions. **c** Single short remnant of a physeal scar

epiphysis for the purpose of forensic age estimation practice. Apart from more precise descriptions and explanations of the ossification stages associated to each question, we supplemented an additional perspective on stage determination by providing descriptions for the "multi-slice view" (MSV). The information of the MSV represents the third dimension of the medial clavicular epiphysis. We believe that not being aware of this information leads to a higher risk of faulty stage determinations.

In 2014, our study group conducted a CT study [34] that revealed, on the one hand, the dependence of clavicular stage determination on specific knowledge and experience of the examiner, and, on the other hand, a number of errors made during the process of stage determination when the short descriptions of the five ossification stages (Table 1) are used exclusively.

The most frequent error made by the inexperienced examiner was the lack of knowledge on the diversity of anatomical shape variants, thereby apparently misleading the inexperienced examiner to classify more cases than actually possible. To address this important result, we included the ban on assessing anatomical shape variants into the preconditions chapter of the present article.

The inexperienced examiner may also have general difficulty as to the differentiation of stage 3 toward the adjacent stages (stage 2 and stage 4). Therefore, question B broaching the issue of fusion areas between metaphysis and EOC was created. Again, the MSV plays an important role regarding this problem because clues for the presence of a stage 3 may be visible on one slice only. If only one slice shows a thin but unambiguous osseous connection between metaphysis and EOC, this is a stage 3 and not a stage 2 anymore. If, on the other hand, there is only one slice that shows (often wedge-shaped) remnants of the epiphyseal cartilage, this is also a stage 3 and still not a stage 4 yet. Of course, a physeal scar may already be visible in a case presenting a late stage 3, but obviously the physeal plate has not ossified completely in those cases. Therefore, the simple presence of a physeal scar cannot be directly and automatically equated to a stage 4. The criterion of the "completely ossified physeal cartilage" must not be neglected. Furthermore, it needs to be stressed that the presence of a stage 3 is generally independent of the size of the EOC.

In order to differentiate between stage 1 (no EOC) and stages 4/5 (complete ossification), question C was included in the algorithm. Forensic age estimation practice suggests that this issue may be a significant problem. To address this point, again the usage of the MSV can be recommended because only if all slices are considered properly, the examiner will be able to translate the total impression (dainty/sharp-edged versus massive/stamp-like) into the correct stage.

Another frequent error was the identification of the physeal scar in a medial clavicular ending which has been ossified completely. This aspect has now been addressed with question D. It should be stressed once more that stage 4 is still existent even if residues of the physeal scar can be recognized on single slices only. Hence, the MSV is of particular importance to avoid overlooking the physeal scar. Stage 5 must not be assumed before the presence of a physeal scar has been excluded in all slices.

In the present article, we have focused on the five main ossification stages according to Schmeling et al. [20] because, in our opinion, the most frequent and the most relevant errors are being made here. Of course, the sub-classification system according to Kellinghaus et al. [21] should not be omitted in modern age diagnostics using CT of the medial clavicular epiphysis. The major source of error in the determination of the sub-stages basically encompasses different approaches when measuring the distances relevant for the assignment of the correct sub-stage [34]. Therefore, it must be emphasized that a measuring tool of the viewing software should be used for all questionable slices; the measurements have to be taken within the most developed and within the same slice; and furthermore, in terms of the sub-stages 3a–c, it is essential to measure the ossified part of the physeal plate and the maximum width of the metaphysis.

Taking all information into account, two general rules may be inferred for the practice of stage determination on the basis of multiple CT slices depicting the medial clavicular epiphysis. These rules result from the strict application of all aspects discussed above and melt down all information into relatively simple formulas:

(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).

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