International Journal of Legal Medicine (2023) 137:1757–1766
https://doi.org/10.1007/s00414-023-03061-7

REVIEW

Standards of practice in forensic age estimation with CT of the medial clavicular epiphysis—a systematic review

Thomas D. Ruder[1] · Saskia C. Kuhnen[1] · Wolf-Dieter Zech[2] · Jeremias B. Klaus[1,2,3] · Paolo Lombardo[1] · Michael Ith[1,4]

Received: 20 March 2023 / Accepted: 8 July 2023 / Published online: 11 September 2023

Abstract
The AGFAD (Arbeitsgemeinschaft für Forensische Alterdiagnostik, Study Group on Forensic Age Diagnostics) has published several recommendations regarding both technical aspects of computed tomography (CT) of the medial clavicular epiphysis (MCE) and the process of reading and interpreting the CT images for forensic age estimations (FAE). There are, however, no published recommendations regarding CT scan protocols and no dose reference values for CT of the MCE. The objective of this analysis was to assess adherence to AGFAD recommendations among practitioners of FAE and analyse reported dose-relevant CT scan parameters with the objective of helping to establish evidence-based dose reference values for FAE. A systematic literature search was conducted in PubMed and in Google Scholar with specific MeSH terms to identify original research articles on FAE with CT of the MCE from 1997 to 2022. A total of 48 studies were included. Adherence to AGFAD recommendations among practitioners of FAE is high regarding the use of Schmeling main stages (93%), bone window (79%), ≤ 1 mm CT slices (67%), axial/coronal CT images (65%), and Kellinghaus sub-stages (59%). The reporting of CT technique and CT dose-relevant scan parameters is heterogeneous and often incomplete in the current literature. Considering the success achieved by the AGFAD in creating standards of practice of FAE in living subjects, there is potential for the AGFAD to establish standards for radiation protection in FAE as well.

Keywords Forensic age estimation · Medial clavicular epiphysis · Computed tomography · CT parameters · Systematic review

Introduction

The AGFAD (Arbeitsgemeinschaft für Forensische Alterdiagnostik, Study Group on Forensic Age Diagnostics) provides guidance on forensic age estimation (FAE) of the living: for FAE in young, potentially minor individuals of uncertified age, radiologic evaluation includes x-ray images of the left hand and teeth to estimate bone and dental age, respectively, as well as computed tomography (CT) of the medial clavicular epiphysis (MCE) in individuals who have reached skeletal maturity of the hand [1–5].

The AGFAD recommends using the Schmeling and Kellinghaus classification systems to evaluate the main stage and sub-stage of MCE ossification on CT scans, and advises that two experts should provide age estimates using mutliplanar reformatted (MPR) axial and coronal images with a slice thickness of 1 mm or less and CT window settings optimized for bone viewing [6–16].

The AGFAD also recommends applying the minimum age concept in the assessment of age estimations to ensure that the age of the person being assessed is not overestimated [3, 5]. This practice also addresses the issue of age mimicry highlighted by Ding [17].

A recent systematic review by Buckley has found that CT currently represents the preferred imaging modality for FAE for many practitioners [18]: CT is more accessible and cost-effective compared to MRI and exhibits lower reader-dependency compared to x-ray and ultrasound. Additionally,

✉ Thomas D. Ruder
thomas.ruder@insel.ch

1 Institute of Diagnostic, Interventional and Pediatric Radiology, Inselspital, Bern University Hospital, University of Bern, Freiburgstrasse, CH-3010 Bern, Switzerland

2 Institute of Forensic Medicine, University of Bern, Bern, Switzerland

3 Roentgen Institute Thun, Thun, Switzerland

4 Radiation Protection, Image Processing Systems & Radiological Processes, Hirslanden Private Hospital Group, Zurich, Switzerland

CT provides a substantial pool of international reference data on the evolution of MCE [6, 18]. The primary limitation of CT imaging is its use of ionizing radiation.

Therefore, radiation protection is a crucial aspect of CT imaging, particularly in the context of FAE where CT is performed for non-medical reasons on a young population, and limiting the scan length to the recommended 4 cm [3, 9, 11, 20–22]) is one way to reduce radiation exposure in FAE [9, 16, 23, 24]. According to the literature, the effective dose values for CT of the MCE, as estimated and calculated, tend to be low, typically below 1 millisievert (mSv), but can vary from 0.2 to 4.6 mSv depending on the scan protocol [11, 15, 16, 21, 22, 24]. There are currently no established dose reference values and no generally accepted scan settings for CT of the MCE for FAE [15, 16].

The objective of this systematic literature review is to (1) assess adherence to AGAFD recommendations among practitioners of FAE and (2) analyse reported dose-relevant CT scan parameters of CT of the MCE for FAE with the objective of helping to establish evidence-based dose reference values for CT of the MCE for FAE.

Method

Literature search

A systematic literature search was conducted in MEDLINE (PubMed) and GoogleScholar. The aim was to identify original research articles on age estimation with CT of the medical clavicular epiphysis. For this purpose, a search equation with the following Medical Subject Headings (MeSH) terms was created for PubMed: ((age estimation OR age determination) AND (clavicular OR clavicle OR medial clavicular epiphysis OR sternoclavicular joints) AND (CT OR CT scan OR computed tomography OR scanner NOT MRI OR magnetic resonance imaging)), filtered by publication date 1997/01/01–2022/11/01. In addition, Pubmed citation searches were conducted for publications citing the following four FAE landmark articles by Kreitner [20], Schmeling [1], and Kellinghaus [8, 27].

Two independent reviewers performed the literature search. The reference lists of all articles assessed for eligibility were searched for additional publications.

Data extraction and analysis

For each of the included studies, the following six categories of information were extracted:

1. Publication information (authors and affiliations, date of (online) publication, journal name, and category, and geographic origin)
2. Indication of CT scans (clinical query, post-mortem investigation, age estimation)
3. Reported CT technique (scanned body region, scan length, position of arms during scan).
4. Reported CT scan parameters (kilovolt (kVp), milliampere-seconds (mAs), use of automatic tube current modulation).
5. Reported radiation dose information (CT dose index (CTDI), dose length product (DLP), and effective dose).
6. Adherence to AGFAD recommendations (use of Schmeling main stages, use Kellinghaus sub-stages, use $\leq$ 1 mm CT slices, use of bone window, use of axial/coronal multiplanar reformats (MPR)).

All parameters were exported for quantitative analysis. Categorical variables and qualitative parameters are expressed as frequencies and percentage (%). Excel (Microsoft Excel, 2010 Microsoft Corporation, Redmond, WA, USA) was used to calculate descriptive statistics.

Results

Literature search

The process of literature identification, screening, eligibility, and inclusion is visualized in the flow diagram below (Fig. 1). The PubMed literature search and the citation search identified 184 and 387 articles, respectively ($n = 571$), with 62 citations for Kreitner's article [20], 169 for Schmeling's article [1], and 79 and 77 citations for the two Kellinghaus articles [8, 27]. The GoogleScholar search identified 978 articles ($n = 978$). After elimination of duplicates, the remaining 802 articles were screened and 56 were included for full-text analysis. Of these, 48 studies were included in the systematic review [7, 8, 10–16, 19, 20, 24–60].

Publication information

Only 7 of all 48 studies (15%) were published during the first half of the study period from 1997 to 2009. Most articles (41/48, 85%) were published between 2010 and 2022. In 32/48 (67%) publications both forensic pathologists and radiologists are involved as co-authors. In 12/48 (25%) and 4/48 (8%) publications there is no affiliation with a radiologic institute or forensic institute, respectively. An overwhelming majority of articles (42/48, 88%) were published in forensic sciences/legal medicine journals. 4/48 articles were published in radiologic journals (8%), 1/48 in a forensic imaging journal (2%). Most publications originated from Europe (26/48, 54%), followed by Asia (16/48, 33%), Australia (4/48, 8%), and Africa (2/48, 4%) (Table 1).

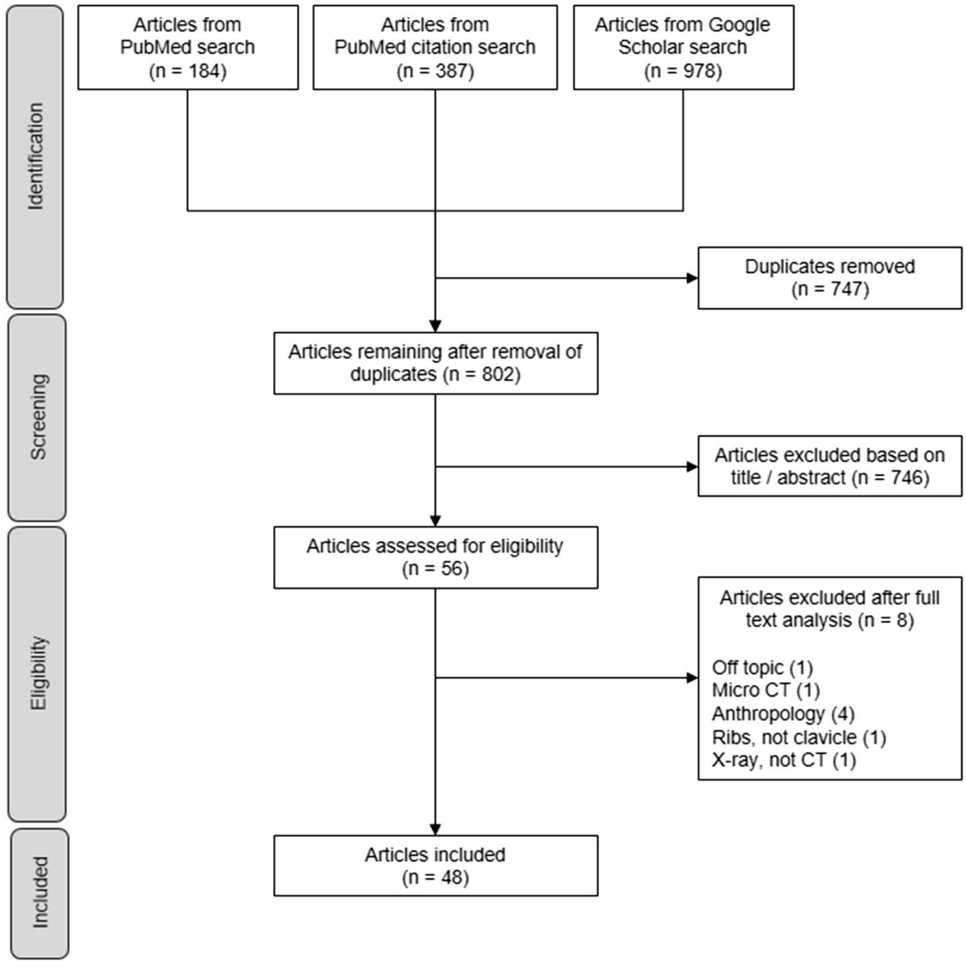

Fig. 1 Flow diagram of literature search and selection process

Indication of CT scans

The indications of CT scans fall into three main categories: clinical query, post-mortem investigation, and age estimation. Clinical CT scans of individuals with known age (26/48, 54%) as well as post-mortem CT (PMCT) scans of individuals with known age (11/48, 23%) were used to establish reference values for age estimation. 11/48 studies (23%) analyzed CT data of individuals that had been scanned for the purpose of FAE in the living (Table 2).

Reported CT technique

The scanned body region was limited to the sternoclavicular joints (SCJ) in 18/48 studies (38%). Among these were all 11 studies of living individuals scanned for FAE, 6 post-mortem studies with PMCTs of excised sternoclavicular joints, and 1 study with clinical CT data, where only "patients undergoing a CT scan of the clavicle" were included. The remaining 25/26 studies with clinical CT data included: chest CT (9/25), multiple trauma CT (4/25), multiple body regions (12/25). Finally, 5/11 post-mortem studies used whole-body PMCT data (Table 2).

Arm position during the CT and scan length were reported in 2/48 (one arms-down, one arms-down vs. arms-up) and 5/48 studies respectively (range: 4–8.5 cm) (Table 4).

Reported CT scan parameter and radiation dose

Reporting of CT scan parameters was heterogeneous: 36/48 (75%) reported kVp, 30/48 (63%) reported mAs (including reporting of mA, reference mAs, and effective mAs), and 15/48 (31%) reported use of automatic tube current modulation. Information regarding CT dose was scarce. Only 5/48 studies report dose parameters [11, 15, 16, 24, 29]. Of these, 3 studies report complete dose information (CTDI, DLP, and effective dose [mSv]) [15, 16, 24], while 2 studies report partial dose information (CTDI and effective dose, respectively) [11, 29]. 12/48 provided no information regarding the CT scan parameters and radiation dose. See Table 3 for an overview of results related to CT scan and dose parameters. See Table 4 for a sub-analysis of the 11 studies with published data on FAE of the living.

Table 1 Overview of publication information

Continent	n	Country	n	Affiliation FM & RX	Affiliation FM	Affiliation RX
Europe	26	Germany	17	[7], [8], [11], [12], [13], [14], [15], [16], [19]*, [20]*, [25], [27], [28], [41]	[34]	[10], [24]*
		Austria	4	[53], [56], [57]		[40]
		France	3	[60]	[46], [47]	
		Denmark	1	[33]#		
		Serbia	1	[37]		
Asia	16	Turkey	6	[39], [44], [48], [51], [52]		[49]*
		India	4	[29], [54], [58]	[41]	
		China	2		[38], [43]	
		Japan	1		[55]	
		Sri Lanka	2	[59]	[50]	
		Thailand	1	[26]		
Australia	4	Australia	4		[30], [31], [32], [41]	
Africa	2	Egypt	2	[35], [44]		

n number of publications for each category, *FM & RX* publications with author affiliations to both institutes of forensic medicine and radiology, *FP* publications with author affiliations to institutes of forensic medicine pathology (but not radiology), *RX* publications with author affiliations to institutes of radiology (but not forensic medicine), *published in radiology journals, #published in forensic radiology journal. Articles without * or # were published in forensic sciences/legal medicine journals

Adherence to AGFAD recommendations

The Schmeling and Kellinghaus classification systems were used in 42/48 (88%) and 22/18, (46%) of all studies, respectively. This translates to 93% of the 45 studies published after Schmeling's article in 2004 and 59% of the 37 studies published after Kellinghaus' article in 2010.

Adherence to recommendations regarding the use of ≤ 1 mm CT slices and axial/coronal reformats has grown in parallel to the evolution of CT technology. Overall, ≤ 1 mm CT were used 32/48 (67%) of studies (of which 28 were published in the last decade) while axial/coronal reformats were used in 31/48, (65%) of studies (26 in the last decade). The use of bone window settings to review CT images of the MCE was documented in 38/48 publications (79%). 10/48 publications [12, 31, 38, 40, 46, 48, 51, 52, 58, 60] provide no information regarding CT image windowing (note that some authors may have viewed images using MPR and bone window, but did not report it in the study) (Table 5).

Discussion

This systematic review on standards of practice in forensic age estimation with CT of the medial clavicular epiphysis has two principal findings: first, there is a

Table 2 Overview of CT indication and scanned body region

Origin of CT data	n	Age	n	Body region	References
Clinical query	26	Known	9	Chest	[24], [37], [42], [46], [48], [49], [51], [52], [58]
			12	Multiple body regions	[10], [19], [20], [26], [29], [36], [38], [39], [44], [47], [54], [59]
			4	Multiple trauma	[7], [8], [27], [35]
			1	SCJ	[43]
Post mortem investigation	11	Known	6	SCJ	[12], [13], [14], [25], [34], [41]
			5	Whole body	[30], [31], [32], [33], [55]
Forensic age estimation	11	Unknown	10	SCJ	[11], [15], [16], [28], [40], [50], [53], [56], [57], [60]
		Known	1	SCJ	[45]

n refers to number of studies per category, *Age* age of individuals in whom age estimation was performed, *SCJ* sternoclavicular joint

Table 3 Reported CT scan parameters and dose parameters

<table>
<tr><th>kVp</th><th>mAs</th><th>automatic mA modulation</th><th>radiation dose information</th><th>none reported</th></tr>
<tr><td colspan="4">Tozakidou [15]*, Tozakidou [16]*, Gassenmaier [24]</td><td rowspan="6">Kreitner [19], Kreitner [20], Pattamapaspong [26], Bassed [30], Bassed [31], Bassed [32], Franklin [42], El Morsi [45]*, Houpert [47], Gunawardena [50]*, Patil [54], Pranavan [59]</td></tr>
<tr><td colspan="3">Kellinghaus [8], Kellinghaus [27], El-Gerby [35], Zhang [43], Gurses [48], Gurses [51], Uysal [52]</td><td></td></tr>
<tr><td colspan="2">Schulz [7], Schulze [10], Wittschieber [12], Wittschieber [13], Scharte [14], Vieth [25], Schulz [28]*, Tangmose [33], Gonsior [34], Gakhar [36], Hua [38], Ekizoglu [39], Wittschieber [41], Ekizoglu [44], Ufuk [49], Torimitsu [55], Shedge [58], Lossois [60]*</td><td rowspan="2"></td><td></td></tr>
<tr><td colspan="2">Mühler [11]*, Kaur [29]</td><td>Mühler [11]*, Kaur [29]</td></tr>
<tr><td>Milenkovic [37], Rudolf [40]*, Rudolf [53]*, Rudolf [56]*, Rudolf [57]*</td><td></td><td>Milenkovic [37], Rudolf [40]*, Rudolf [53]*, Rudolf [56]*, Rudolf [57]*</td><td></td></tr>
<tr><td>Houpert [46]</td><td></td><td></td><td></td></tr>
</table>

kVp kilovolt peak (tube potential); *mAs* milliampere-second (tube current - time product); *mA* milliampere (tube current); * studies on age estimation in the living. Reading example: Studies [15] and [16] reported kVp, mAs, use of DMS, and Dose parameters, while [11] reported kVp, mAs, Dose parameters, but not if DMS was used

considerable level of international standardization in the practice of FAE with CT of the MCE due to high adherence to AGFAD recommendations, and second, reporting of CT technique and CT dose-relevant scan parameters is heterogeneous and often incomplete in the current literature.

These results are relevant because they show how the AGFAD could contribute to the creation of new practice standards regarding dose optimisation for CT of the MCE.

A key finding of this analysis is that reporting of CT technique and scan parameters is incomplete in many studies on CT of clavicles for FAE. The primary reason for this is that

Table 4 Reported CT scan parameters and dose parameters of FAE studies

Author	Published (online)	CT scanner	Arm position	Scan lenght [cm]	kVp	mA/mAs	Automatic mA modulation	Effective dose [mSv]	DLP [mGy*cm]
Mühler [11]	2005	1-slice	Not rep	4	120	130 mA	Not rep	0.5*	Not rep
Schulz [28]	2007	1-slice	Not rep	4	120	130 mA	Not rep	Not rep	Not rep
El Morsi [45]	2015	"Multi-slice CT"	Not rep	Not rep	np	Not rep	Not rep	Not rep	Not rep
Gunawardena [50]	2016	64-slice	Not rep	Not rep	np	Not rep	Not rep	Not rep	Not rep
Rudolf [40]	2014	16-slice	Not rep	Not rep	130	Not rep	Used	Not rep	Not rep
Rudolf [53]	2017	16-slice	Not rep	Not rep	130	Not rep	Used	Not rep	Not rep
Rudolf [56]	2019	16-slice	Not rep	Not rep	130	Not rep	Used	Not rep	Not rep
Rudolf [57]	2019	16-slice	Not rep	Not rep	130	Not rep	Used	Not rep	Not rep
Tozakidou [15]	2019	256-slice	Down	6.2 ± 2.1	140	70 mAs ref	Used	0.95 ± 0.38	69.5 ± 27.6
Tozakidou [16]	2021	256-slice	Down	6.2 ± 2.1	140	70 mAs ref	Used	0.95 ± 0.38	69.5 ± 27.6
			Up	8.5 ± 3.4	140	70 mAs ref	Used	0.79 ± 0.32	57.5 ± 23.4
Lossois [60]	2022	64-slice	Not rep	4	120	200 mAs eff	Not rep	Not rep	Not rep

kVp kilovolt peak (tube potential), *mA* milliampere (tube current), *mAs* milliampere-second (tube current–time product), *calculated dose for a patient of 70 kg

Table 5 Adherence to AGFAD recommendations

<table>
<tr><th>use of Schmeling main stages</th><th>use of Kellinghaus sub-stages</th><th>use of ≤1 mm CT slices</th><th>ax/cor MPR[1]</th><th>bone window[2]</th></tr>
<tr><td colspan="5">Wittschieber [13], Scharte [14], Tozakidou [15]*, Tozakidou [16]*, Gassenmaier [25], Pattamapaspong [26], Houpert [47], Gunawardena [50]*, Rudolf [53]*, Torimitsu [55], Rudolf [57]*</td></tr>
<tr><td colspan="4">Wittschieber [12], Rudolf [40]*, Houpert [46], Gurses [48], Gurses [51], Uysal [52], Lossois [60]*</td><td></td></tr>
<tr><td colspan="3">Wittschieber [41], Ekizoglu [44], Shedge [58]</td><td></td><td>Schulze [10], Kreitner [19], Kreitner [20], Wittschieber [41], Ekizoglu [44]</td></tr>
<tr><td colspan="2">Kellinghaus [8]</td><td></td><td colspan="2">Kellinghaus [8]</td></tr>
<tr><td>Kellinghaus [27], Bassed [30], Bassed [32], Milenkovic [37], Franklin [42], Ufuk [49]</td><td></td><td></td><td colspan="2">Kellinghaus [27], Bassed [30], Bassed [32], Milenkovic [37], Franklin [42], Ufuk [49]</td></tr>
<tr><td>Tangmose [33], Zhang [43], Patil [54]</td><td></td><td colspan="3">Tangmose [33], Gonsior [34], Zhang [43], Patil [54], Rudolf [56]*</td></tr>
<tr><td>Schulz [7], Mühler [11]*, Vieth [25], Schulz [28]*, Kaur [29], Bassed [31], El-Gerby [35], Gakhar [36], Ekizoglu [39], El Morsi [45]*, Pranavan [59]</td><td></td><td>Mühler [11]*, Vieth [23], Schulz [28]*, Kaur [29], Hua [38], Ekizoglu [39]</td><td>Bassed [31]</td><td>Schulz [7], Mühler [11]*, Vieth [25], Schulz [28]*, Kaur [29], El-Gerby [35], Gakhar [36], Ekizoglu [39], El Morsi [45]*</td></tr>
</table>

[1]use axial and coronal MPR images reported in study; [2] use of bone window in study; * studies on age estimation in the living. Note: some authors may have viewed images using MPR and bone window, but did not report it in the study. Reading example: [41] used both Schmeling main and Kellinghaus sub-stages, and viewed CT images of ≤ 1 mm thickness in a bone window, but they did not report the use of axial and coronal MPR image. [10] used bone window for viewing images

more than half of the publications on this topic are reference studies that rely on clinical CT scans of mixed body regions, mixed scan lengths, and therefore mixed CT settings [7, 8, 10, 19, 20, 24, 26, 27, 29, 35–39, 42, 44, 46–49, 51, 52, 54, 58, 59]. Extracting radiation exposure parameters that are meaningful to dedicated CT examinations of the MCE from these data is very challenging. CT scan parameters from post-mortem reference studies are also difficult to transfer to FAE in the living. Although PMCT protocols do not use unreasonable high radiation doses, radiation protection is not a concern in PMCT.

Therefore, the most relevant source of information for guidance on CT technique and scan parameters is those 11 studies that used CT data from CTs of the MCE for actual FAE.

Nine of these do report dose-relevant parameters in their material and methods (two do not) and the specified CT parameters are a good starting point for future work in this field. It is, however, important to keep in mind that of these nine studies, two [11, 28] are more than 15 years old, which is a long time in CT technology. Of the remaining seven studies, four were authored by Rudolf et al. [40, 53, 56, 57], two by Tozakidou et al. [15, 16], and one by Lossois et al. [60]. This means that the available, up-to-date data on CT scan parameters of the MCE for FAE is based on the work of 3 authors only, of which only 1 author had a focus on dose optimisation [15, 16]. These data are insufficient for proposing evidence-based dose reference values for CT of the MCE for FAE.

One important parameter in dose optimisation is arm positioning during CT. According to Tozakidou et al., it is common practice to perform CT of the MCE for FAE in an arms-down position [16]. This systematic review was unable to confirm or deny this practice, because only 2 of all included studies had explicitly reported arm position during CT [15, 16]. The presence of arms within the scan range increases patient dose (more dose required to penetrate humerus) and decreases image quality (more noise from beam hardening artifacts). Clinical practice is therefore to position patient arms outside of the scan range whenever possible, e.g., arms up for chest CT and arms down for neck/c-spine CTs [61–64].

The practice of CT of the MCE with arms down may represent a holdover from the time when age estimations were performed with x-rays of the clavicle (taken in an arms-down position) and should be revaluated in the current era of CT. In this context, one must keep in mind that many CT reference studies for FAE are based on clinical CT scans, often the chest [24, 36, 37, 42, 46, 48, 49, 51, 52, 58]—scanned with arms raised—and therefore, a change in practice to CT of the clavicle with arms-up for age estimation is unlikely to have an effect on staging of MCE ossification. Recently, Tozakidou has already demonstrated how CT of the MCE for FAE with arms up has the potential to decrease effective dose and increases image quality [16].

Finally, another key finding of this analysis is that adherence to AGFAD recommendations is high among practitioners of FAE. Today, the following 5 AGFAD recommendations for age estimation with CT of the clavicles have become internationally recognized standards of practice: (1) use Schmeling main stages (93% adherence after 2004); (2) use of Kellinghaus sub-stages (59% adherence after 2010); (3) use ≤ 1 mm CT images (88% adherence after 2011); (4) use of axial/coronal reformats (80% adherence since 2013); and (5) use of the bone window (documented in 79% of studies).

The fact that the AGFAD has established internationally recognized standards of practice regarding both technical aspects of CT and the process of carrying out the forensic age estimations underlines the potential the AGFAD has to also introduce standards in radiation protection. The fact that the vast majority of publications on FAE with CT of MCE are collaborations between authors with a forensic and authors with a radiologic background is also beneficial to achieve this aim.

Over the past few years, three publications have demonstrated how clinically established dose reduction strategies such as iterative CT reconstruction, arm position outside the scan field, and low dose CT can be transferred to FAE [15, 16, 21].

A recent cadaver study has tested how low CT dose may be lowered while maintaining diagnostic image quality for age estimation [65]. The authors have managed to reduce the dose to approximately 0.15 mSv (calculation with conversion factor of 0.0137 [16]) (using both a fixed parameters protocol at 100 kVp and 30 mAs and a protocol with 120 kVp and automatic dose modulation with 40 mAs reference. These preliminary results indicate that the dose of CT of the MCE may be substantially lowered while still maintaining diagnostic image quality.

Conclusions

Over the past 2 decades, the AGFAD has published several recommendations regarding both technical aspects of CT and the process of carrying out forensic age estimations that have become internationally accepted standards of practice.

The reporting of dose-relevant CT techniques and CT scan parameters in the literature on FAE is heterogeneous and often incomplete regarding data on dose-relevant CT parameters. Based on the available information, it is not possible yet to propose evidence-based reference values for CT of the MCE for FAE.

In view of the success achieved by the AGFAD in standardizing the practice of FAE in the living, the AGFAD has to potential to establish standards in radiation protection for FAE as well, for example through publishing best practice recommendations for radiation dose optimization.

Funding Open access funding provided by University of Bern.

Declarations

Ethical approval Ethics board approval or written informed consent was not required/not applicable for this systematic review.

Conflict of interest The authors declare no competing interests.

References

1. Schmeling A, Grundmann C, Fuhrmann A, Kaatsch HJ, Knell B, Ramsthaler F, Reisinger W, Riepert T, Ritz-Timme S, Rösing FW, Rötzscher K, Geserick G (2008) Criteria for age estimation in living individuals. Int J Legal Med. https://doi.org/10.1007/s00414-008-0254-2
2. Wittschieber D, Ottow C, Vieth V, Küppers M, Schulz R, Hassu J, Bajanowski T, Püschel K, Ramsthaler F, Pfeiffer H, Schmidt S, Schmeling A (2015) Projection radiography of the clavicle: still recommendable for forensic age diagnostics in living individuals? Int J Legal Med. https://doi.org/10.1007/s00414-014-1067-0
3. Schmeling A, Dettmeyer R, Rudolf E, Vieth V, Geserick G (2016) Forensic age estimation. Dtsch Arztebl Int. https://doi.org/10.3238/arztebl.2016.0044
4. Arbeitsgruppe für Forensische Altersdiagnostik (AGFAD) (2018) Forensische Altersdiagnostik bei unbegleiteten minderjährigen Flüchtlingen. Arbeitsgemeinschaft für Forensische Altersdiagnostik. https://www.dgrm.de/institute/deutschland/essen/stellungnahme-forensische-altersdiagnostik-bei-unbegleiteten-minderjaehrigen-fluechtlingen. Accessed 27 February 2023
5. Schmeling A, Kreitner KF, Heindel W, Vieth V (2019) Imaging methods used for forensic age assessment in juveniles and young adults. Radiologie Up2date. https://doi.org/10.1055/a-0795-1838
6. Schmeling A, Schulz R, Reisinger W, Mühler M, Wernecke KD, Geserick G (2004) Studies on the time frame for ossification of the medial clavicular epiphyseal cartilage in conventional radiography. Int J Legal Med. https://doi.org/10.1007/s00414-003-0404-5

7. Schulz R, Mühler M, Mutze S, Schmidt S, Reisinger W, Schmeling A (2005) Studies on the time frame for ossification of the medial epiphysis of the clavicle as revealed by CT scans. Int J Legal Med. https://doi.org/10.1007/s00414-005-0529-9
8. Kellinghaus M, Schulz R, Vieth V, Schmidt S, Pfeiffer H, Schmeling A (2010) Enhanced possibilities to make statements on the ossification status of the medial clavicular epiphysis using an amplified staging scheme in evaluating thin-slice CT scans. Int J Legal Med. https://doi.org/10.1007/s00414-010-0448-2
9. Hermetet C, Saint-Martin P, Gambier A, Ribier L, Sautenet B, Rérolle C (2018) Forensic age estimation using computed tomography of the medial clavicular epiphysis: a systematic review. Int J Legal Med. https://doi.org/10.1007/s00414-018-1847-z
10. Schulze D, Rother U, Fuhrmann A, Richel S, Faulmann G, Heiland M (2006) Correlation of age and ossification of the medial clavicular epiphysis using computed tomography. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2005.05.033
11. Mühler M, Schulz R, Schmidt S, Schmeling A, Reisinger W (2006) The influence of slice thickness on assessment of clavicle ossification in forensic age diagnostics. Int J Legal Med. https://doi.org/10.1007/s00414-005-0010-9
12. Wittschieber D, Schulz R, Vieth V, Küppers M, Bajanowski T, Ramsthaler F, Püschel K, Pfeiffer H, Schmidt S, Schmeling A (2014) The value of sub-stages and thin slices for the assessment of the medial clavicular epiphysis: a prospective multi-center CT study. Forensic Sci Med Pathol. https://doi.org/10.1007/s12024-013-9511-x
13. Wittschieber D, Schulz R, Vieth V, Küppers M, Bajanowski T, Ramsthaler F, Püschel K, Pfeiffer H, Schmidt S, Schmeling A (2014) Influence of the examiner's qualification and sources of error during stage determination of the medial clavicular epiphysis by means of computed tomography. Int J Legal Med. https://doi.org/10.1007/s00414-013-0932-6
14. Scharte P, Vieth V, Schulz R, Ramsthaler F, Püschel K, Bajanowski T, Pfeiffer H, Schmeling A, Schmidt S, Wittschieber D (2017) Comparison of imaging planes during CT-based evaluation of clavicular ossification: a multi-center study. Int J Legal Med. https://doi.org/10.1007/s00414-017-1615-5
15. Tozakidou M, Apine I, Petersen KU, Weinrich JM, Schindera S, Jopp-van Well E, Püschel K, Herrmann J (2020) Comparison of different iterative CT reconstruction techniques and filtered back projection for assessment of the medial clavicular epiphysis in forensic age estimation. Int J Legal Med. https://doi.org/10.1007/s00414-019-02214-x
16. Tozakidou M, Meister RL, Well L, Petersen KU, Schindera S, Jopp-van Well E, Püschel K, Herrmann J (2021) CT of the medial clavicular epiphysis for forensic age estimation: hands up? Int J Legal Med. https://doi.org/10.1007/s00414-021-02516-z
17. Ding KY, Rolseth V, Dahlberg PS, Mosdøl A, Straumann GH, Bleka Ø, Vist GE (2018) Systematic review: age estimation by ossification stages of the medial clavicular epiphysis. Norwegian Institute of Public Health: https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2018/age-estimation-by-ossification-stages-of-the-medial-clavicular-epiphysis-rapport-2018-v3.pdf. Accessed 3 Jul 2023
18. Buckley MB, Clark KR (2017) Forensic age estimation using the medial clavicular epiphysis: a study review. Radiol Technol 88(5):482–498
19. Kreitner KF, Schweden FJ, Schild HH, Riepert T, Nafe B (1997) The epiphyseal union of the medial clavicle determined by CT-an axillary method in age identification during adolescence and 3rd decade of life? Rofo. https://doi.org/10.1055/s-2007-1015463
20. Kreitner KF, Schweden FJ, Riepert T, Nafe B, Thelen M (1998) Bone age determination based on the study of the medial extremity of the clavicle. Eur Radiol. https://doi.org/10.1007/s003300050518
21. Ramsthaler F, Proschek P, Betz W, Verhoff MA (2009) How reliable are the risk estimates for X-ray examinations in forensic age estimations? A safety update. Int J Legal Med. https://doi.org/10.1007/s00414-009-0322-2
22. Meier N, Schmeling A, Loose R, Vieth V (2015) Age diagnostics and radiation exposure. Rechtsmedizin. https://doi.org/10.1007/s00194-014-1005-y
23. The Royal College of Radiologists (2020) IR(ME)R: implications for clinical practice in diagnostic imaging, interventional radiology and diagnostic nuclear medicine. IOP Publishing RCR AC. https://www.rcr.ac.uk/publication/irmer-implications-diagnostic-imaging-interventional-radiology-diagnostic-nuclear-medicine. Accessed 27 Feb 2023
24. Gassenmaier S, Schaefer JF, Nikolaou K, Esser M, Tsiflikas I (2020) Forensic age estimation in living adolescents with CT imaging of the clavicula-impact of low-dose scanning on readers' confidence. Eur Radiol. https://doi.org/10.1007/s00330-020-07079-y
25. Vieth V, Kellinghaus M, Schulz R, Pfeiffer H, Schmeling A (2010) Ossification stage of the medial clavicular epiphysis: comparison of projectional radiography, computed tomograhpy and magnetic resonance imaging. Rechtsmedizin. https://doi.org/10.1007/s00194-010-0709-x
26. Pattamapaspong N, Madla C, Mekjaidee K, Namwongprom S (2015) Age estimation of a Thai population based on maturation of the medial clavicular epiphysis using computed tomography. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2014.10.044
27. Kellinghaus M, Schulz R, Vieth V, Schmidt S, Schmeling A (2010) Forensic age estimation in living subjects based on the ossification status of the medial clavicular epiphysis as revealed by thin-slice multidetector computed tomography. Int J Legal Med. https://doi.org/10.1007/s00414-009-0398-8
28. Schulz R, Mühler M, Reisinger W, Schmidt S, Schmeling A (2008) Radiographic staging of ossification of the medial clavicular epiphysis. Int J Legal Med. https://doi.org/10.1007/s00414-007-0210-6
29. Kaur G, Khandelwal N, Jasuja OP (2010) Computed tomographic studies on ossification status of medial epiphysis of clavicle: effect of slice thickness and dose distribution. J Indian Acad Forensic Med 32:298–302
30. Bassed RB, Drummer OH, Briggs C, Valenzuela A (2011) Age estimation and the medial clavicular epiphysis: analysis of the age of majority in an Australian population using computed tomography. Forensic Sci Med Pathol. https://doi.org/10.1007/s12024-010-9200-y
31. Bassed RB, Briggs C, Drummer OH (2011) Age estimation using CT imaging of the third molar tooth, the medial clavicular epiphysis, and the spheno-occipital synchondrosis: a multifactorial approach. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2011.06.007
32. Bassed RB, Briggs C, Drummer OH (2012) The incidence of asymmetrical left/right skeletal and dental development in an Australian population and the effect of this on forensic age estimations. Int J Legal Med. https://doi.org/10.1007/s00414-011-0621-2
33. Tangmose S, Jensen KE, Lynnerup N (2013) Comparative study on developmental stages of the clavicle by postmortem MRI and CT imaging. J Forensic Radiol Imaging. https://doi.org/10.1016/j.jofri.2013.05.008
34. Gonsior M, Ramsthaler F, Gehl A, Verhoff MA (2013) Morphology as a cause for different classification of the ossification stage of the medial clavicular epiphysis by ultrasound, computed tomography, and macroscopy. Int J Legal Med. https://doi.org/10.1007/s00414-013-0889-5

35. El-Gerby KM, Mohammed AS, Gomaa MS (2013) Using thin-slice multidetector computed tomography in forensic age estimation based on the ossification status of the medial clavicular epiphysis among Egyptian subjects. Med J Cairo Univ 81:221–227
36. Gakhar GA, Jasuja OP, Khandelwal N (2014) Determining the ossification status of sternal end of the clavicle using CT and digital x-ray: a comparative study. J Forensic Res 5:223. https://doi.org/10.4172/2157-7145.1000223
37. Milenkovic P, Djuric M, Milovanovic P, Djukic K, Zivkovic V, Nikolic S (2014) The role of CT analyses of the sternal end of the clavicle and the first costal cartilage in age estimation. Int J Legal Med. https://doi.org/10.1007/s00414-014-1026-9
38. Hua W, Guang-you Z, Lei W, Chong-liang Y, Ya-hui W (2014) Correlation between age and the parameters of medial epiphysis and metaphysis of the clavicle using CT volume rendering images. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2014.09.006
39. Ekizoglu O, Hocaoglu E, Inci E, Sayin I, Solmaz D, Bilgili MG, Can IO (2015) Forensic age estimation by the Schmeling method: computed tomography analysis of the medial clavicular epiphysis. Int J Legal Med. https://doi.org/10.1007/s00414-014-1121-y
40. Rudolf E, Kramer J, Gebauer A, Bednar A, Recsey Z, Zehetmayr J, Bukal J, Winkler I (2015) Standardized medical age assessment of refugees with questionable minority claim-a summary of 591 case studies. Int J Legal Med. https://doi.org/10.1007/s00414-014-1122-x
41. Wittschieber D, Schmidt S, Vieth V, Schulz R, Püschel K, Pfeiffer H, Schmeling A (2014) Subclassification of clavicular substage 3a is useful for diagnosing the age of 17 years. Rechtsmedizin. https://doi.org/10.1007/s00194-014-0990-1
42. Franklin D, Flavel A (2015) CT evaluation of timing for ossification of the medial clavicular epiphysis in a contemporary Western Australian population. Int J Legal Med. https://doi.org/10.1007/s00414-014-1116-8
43. Zhang K, Chen XG, Zhao H, Dong XA, Deng ZH (2015) Forensic age estimation using thin-slice multidetector ct of the clavicular epiphyses among adolescent western Chinese. J Forensic Sci. https://doi.org/10.1111/1556-4029.12739
44. Ekizoglu O, Hocaoglu E, Inci E, Can IO, Aksoy S, Sayin I (2015) Estimation of forensic age using substages of ossification of the medial clavicle in living individuals. Int J Legal Med. https://doi.org/10.1007/s00414-015-1234-y
45. El Morsi DA, El-Atta HMA, Elmaadawy M, Tawfik AM, Batouty NH (2015) Age estimation from ossification of the medial clavicular epiphysis by computed tomography. Int J Morphol. https://doi.org/10.4067/S0717-95022015000400038
46. Houpert T, Rérolle C, Savall F, Telmon N, Saint-Martin P (2016) Is a CT-scan of the medial clavicle epiphysis a good exam to attest to the 18-year threshold in forensic age estimation? Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2015.12.007
47. Houpert T, Rerolle C, Telmon N, Saint-Martin P (2016) Contribution du scanner de l'extrémité sternale de la clavicule dans l'estimation de l'âge du sujet vivant CT-scan of the medial clavicle epiphysis and forensic age estimation. La Revue de Médecine Légale. https://doi.org/10.1016/j.medleg.2015.10.003
48. Gurses MS, Inanir NT, Gokalp G, Fedakar R, Tobcu E, Ocakoglu G (2016) Evaluation of age estimation in forensic medicine by examination of medial clavicular ossification from thin-slice computed tomography images. Int J Legal Med. https://doi.org/10.1007/s00414-016-1408-2
49. Ufuk F, Agladioglu K, Karabulut N (2016) CT evaluation of medial clavicular epiphysis as a method of bone age determination in adolescents and young adults. Diagn Interv Radiol. https://doi.org/10.5152/dir.2016.15355
50. Gunawardena SA, Liyanage UA, Weeratna JB, Mendis NDNA, Perera HJM, Jayasekara RW, Fernando R (2017) Forensic age estimation in anti-piracy trials in Seychelles: experiences and challenges faced. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2016.11.010
51. Gurses MS, Inanir NT, Soylu E, Gokalp G, Kir E, Fedakar R (2017) Evaluation of the ossification of the medial clavicle according to the Kellinghaus substage system in identifying the 18-year-old age limit in the estimation of forensic age-is it necessary? Int J Legal Med. https://doi.org/10.1007/s00414-016-1515-0
52. Uysal Ramadan S, Gurses MS, Inanir NT, Hacifazlioglu C, Fedakar R, Hizli S (2017) Evaluation of the medial clavicular epiphysis according to the Schmeling and Kellinghaus method in living individuals: a retrospective CT study. Leg Med (Tokyo). https://doi.org/10.1016/j.legalmed.2016.12.012
53. Rudolf E, Kramer J, Schmidt S, Vieth V, Winkler I, Schmeling A (2018) Intraindividual incongruences of medially ossifying clavicles in borderline adults as seen from thin-slice CT studies of 2595 male persons. Int J Legal Med. https://doi.org/10.1007/s00414-017-1694-3
54. Patil PB, Kiran R, Maled V, Dakhankar S (2018) The chronology of medial clavicle epiphysis ossification using computed tomography. IJARS. https://doi.org/10.7860/IJARS/2018/32595:2357
55. Torimitsu S, Makino Y, Saitoh H, Ishii N, Inokuchi G, Motomura A, Chiba F, Yamaguchi R, Hoshioka Y, Urabe S, Iwase H (2019) Age estimation based on maturation of the medial clavicular epiphysis in a Japanese population using multidetector computed tomography. Leg Med (Tokyo). https://doi.org/10.1016/j.legalmed.2018.12.003
56. Rudolf E, Kramer J, Winkler I, Schmeling A (2019) Technical note: utilization of 3D-rendering for CT evaluation of extremitas sternalis claviculae within medical age assessment practice. Int J Legal Med. https://doi.org/10.1007/s00414-019-02025-0
57. Rudolf E, Kramer J, Schmidt S, Vieth V, Winkler I, Schmeling A (2019) Anatomic shape variants of extremitas sternalis claviculae as collected from sternoclavicular thin-slice CT-studies of 2820 male borderline-adults. Int J Legal Med. https://doi.org/10.1007/s00414-019-02065-6
58. Shedge R, Kanchan T, Garg PK, Dixit SG, Warrier V, Khera P, Krishan K (2020) Computed tomographic analysis of medial clavicular epiphyseal fusion for age estimation in Indian population. Leg Med (Tokyo). https://doi.org/10.1016/j.legalmed.2020.101735
59. Pranavan S, Kalubowila KC, Senanayake G, Liyanage UA, Gunawardena SA (2022) The pattern of medial clavicular epiphyseal ossification: preliminary study of a Sri Lankan population. SLJFMSL. https://doi.org/10.4038/sljfmsl.v11i1.7836
60. Lossois M, Cyteval C, Baccino E, Peyron PA (2022) Forensic age assessments of alleged unaccompanied minors at the Medicolegal Institute of Montpellier: a 4-year retrospective study. Int J Legal Med. https://doi.org/10.1007/s00414-022-02813-1
61. Brink M, de Lange F, Oostveen LJ, Dekker HM, Kool DR, Deunk J, Edwards MJR, van Kuijk C, Kamman RL, Blickman JG (2008) Arm raising at exposure-controlled multidetector trauma CT of thoracoabdominal region: higher image quality, lower radiation dose. Radiology. https://doi.org/10.1148/radiol.2492080169
62. Marsh RM, Silosky MS (2017) The effects of patient positioning when interpreting CT dose metrics: a phantom study. Med Phys. https://doi.org/10.1002/mp.12137
63. Euler A, Szücs-Farkas Z, Schindera S (2014) Options for radiation dose reduction in CT. Radiologie. https://doi.org/10.1055/s-0034-1365687
64. Tozakidou M, Yang SR, Kovacs BK, Szucs-Farkas Z, Studler U, Schindera S, Hirschmann A (2019) Dose-optimized computed

tomography of the cervical spine in patients with shoulder pull-down: is image quality comparable with a standard dose protocol in an emergency setting? Eur Radiol. https://doi.org/10.1016/j.ejrad.2019.108655
65. Mehnert S, Berger N, Flach PM, Thali MJ, Ampanozi G, Franckenberg S (2023) How low can we go? CT dose reduction in the assessment of the medial clavicular epiphysis in forensic age estimation: a prospective postmortem CT study. Acta Radiol.https://doi.org/10.1177/02841851231164996