European Radiology (2019) 29:2311–2321
https://doi.org/10.1007/s00330-018-5761-z

FORENSIC MEDICINE

Age assessment by Demirjian's development stages of the third molar: a systematic review

Veslemøy Rolseth[1] · Annhild Mosdøl[2] · Pål Skage Dahlberg[1] · Yunpeng Ding[2] · Øyvind Bleka[1] · Marianne Skjerven-Martinsen[1] · Gyri Hval Straumann[2] · Gerd Jorunn Møller Delaveris[1] · Gunn Elisabeth Vist[2]

Received: 30 April 2018 / Revised: 21 August 2018 / Accepted: 13 September 2018 / Published online: 30 November 2018

Abstract

Objectives Radiographic evaluation of the wisdom teeth (third molar) formation is a widely used age assessment method for adolescents and young adults. This systematic review examines evidence on the agreement between Demirjian's development stages of the third molar and chronological age.

Methods We searched four databases up until May 2016 for studies reporting Demirjian's stages of third molar and confirmed chronological age of healthy individuals aged 10–25 years. Heterogeneity test of the included studies was performed.

Results We included 21 studies from all continents except Australia, all published after 2005. The mean chronological age for Demirjian's stages varied considerably between studies. The results from most studies were affected by age mimicry bias. Only a few of the studies based their results on an unbiased age structure, which we argue as important to provide an adequate description of the method's ability to estimate age.

Conclusion Observed study variation in the timing of Demirjian's development stages for third molars has often been interpreted as differences between populations and ethnicities. However, we consider age mimicry to be a dominant bias in these studies. Hence, the scientific evidence is insufficient to conclude whether such differences exist.

Key Points

- *There is significant heterogeneity between studies evaluating age assessment by Demirjian's third molar development.*
- *Most of the studies were subject to the selection bias age mimicry which can be a source of heterogeneity.*
- *Presence of age mimicry bias makes it impossible to compare and combine results. These biased studies should not be applied as reference studies for age assessment.*

Keywords Age determination by teeth · Molar, third · Odontogenesis · Adolescent · Young adult

Abbreviations

CA Chronological age
PI Prediction interval

Introduction

Age assessment in the living is important in today's society as almost one third of all births worldwide are not registered [1]. It is particularly important to distinguish children from adults, since status as a minor brings forth specific rights for protection, for instance in asylum cases. Age estimation in children and adolescents is often performed by assessment of skeletal hand-wrist or tooth development [2]. The most prevalent tooth formation system is described by Demirjian, Goldstein, and Tanner (later called Demirjian's stages) [3]. In late teens, the only developing teeth are the third molars, and hence, the only teeth relevant for age assessment in this age group.

Demirjian's stages of tooth formation are a simplified and modified version of the stages published by Moorrees,

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00330-018-5761-z) contains supplementary material, which is available to authorized users.

✉ Veslemøy Rolseth
vesrol@ous-hf.no

[1] Department of Forensic Sciences, Oslo University Hospital, P.O. Box 4950, Nydalen, 0424 Oslo, Norway

[2] Division for health services, Norwegian Institute of Public Health, Oslo, Norway

Fanning, and Hunt in 1963 [4]. Demirjian's development stages classify and divide the calcification of root and crown into eight stages (A to H). Originally, Demirjian only studied the first seven teeth; however, in 1993, Mincer et al established Demirjian's grading system for the third molar [5]. Since then, several validation studies on Demirjian's development stages of the third molar have been published. Some of these studies are used as a basis to assess age of young asylum seekers with unverified age. These studies usually present mean chronological age with variance for each development stage, often representing a specific population with limited number of individuals in each stage.

The objective of this systematic review is to assess the scientific evidence on the agreement between Demirjian's stages of wisdom teeth and chronological age, and if possible to elucidate any variations between different populations. We chose to focus on Demirjian's formation stages as this grading system is the most widely used for age estimation in children and young adults. In parallel, we also conducted a systematic review on age estimation based on skeletal hand maturation stages from the Greulich and Pyle atlas ("A systematic review of the agreement between chronological age and skeletal age based on the Greulich and Pyle atlas" by Dahlberg et al [6]).

Material and methods

We conducted this systematic review guided by the Cochrane Handbook for Systematic Reviews [7] and PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) [8], using a pre-defined protocol. Full details of search strategy can be found in a technical report [9].

Search strategy and study selection

In May 2016, we searched for primary studies in the Cochrane Central Register of Controlled Trials (CENTRAL), MEDLINE (Ovid) and PubMed [sb], Embase (Ovid), and Google Scholar with no restrictions on publication date or language. The search strategy was peer reviewed. This search was a joint search for four systematic reviews on age assessment: one on the Greulich and Pyle hand-wrist atlas, the present on third molar formation, another on the medial clavicle ossification, and the last on knee and ankle ossification. Hence, the search covered studies that use radiographs of teeth or hand-wrist, and CT or MRI of the clavicle, knee, and ankle for age assessment of children and young adults between 10 and 25 years. Pairs among the authors independently screened the identified references from title and abstract, subsequently in full text, for potentially eligible publications for age estimation using dental radiographs. Studies were eligible if they reported mean chronological age with variance for all or some of Demirjian's third molar stages in healthy individuals and presented number of persons in each stage. Exclusion criteria were (a) the absence of a full-text report and (b) fewer than 50 participants in the predetermined age range as mentioned above.

Quality assessment

Two of the authors independently considered the risk of bias in the included studies based on the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) checklist and summarised this jointly. QUADAS-2 consists of four key domains covering patient selection, index test, reference standard, and flow of patients through the study and timing of the index test and reference standard.

When age assessment is based on the direct probability distributions of age in each development stage, the estimate is highly influenced by the age span and sample size in each age group of the reference population. This effect is called age mimicry [10, 11]. The intention of many studies is to provide results for further analysis: study comparisons or age assessment in other populations. We considered the extracted data as biased in the age mimicry domain if the reference sample was non-uniformly distributed on age and/or the age span was not appropriate. Selection bias is covered in the first domain by QUADAS-2 where we added two extra signaling questions: (1) whether the age span was wide enough to cover all possible ages for the described Demirjian's stages of the third molar and (2) if the number of subjects in each age group was equal or nearly equal.

Data extraction and statistical analysis

For each included study, we extracted mean chronological age with variance and number of subjects in each Demirjian's third molar stage presented. The 95% confidence intervals (95% CI) of the population means and inference of heterogeneity between studies were calculated by the statistical software R (version 3.3.2) with the R-package "metafor."

In order to apply Demirjian's stages of the third molar to assess chronological age, mean age and confidence interval of the mean are considered inadequate due to the biological variation between individuals. To illustrate the age variation within each Demirjian's stage, we calculated 95% prediction intervals (95% PI) of age by assuming a normal distribution (as done by Chaumoitre et al [12]) based on results from the largest study with an adequate study design [13]. A 95% PI is an estimate of an interval in which a future observation, coming from the same population, will fall inside with 95% probability.

To verify the effect of one of the contributors to age mimicry bias—the age span of the reference sample—we present a frequency table using data from the same study [13]. Hence, we recalculated the mean age for each stage using different

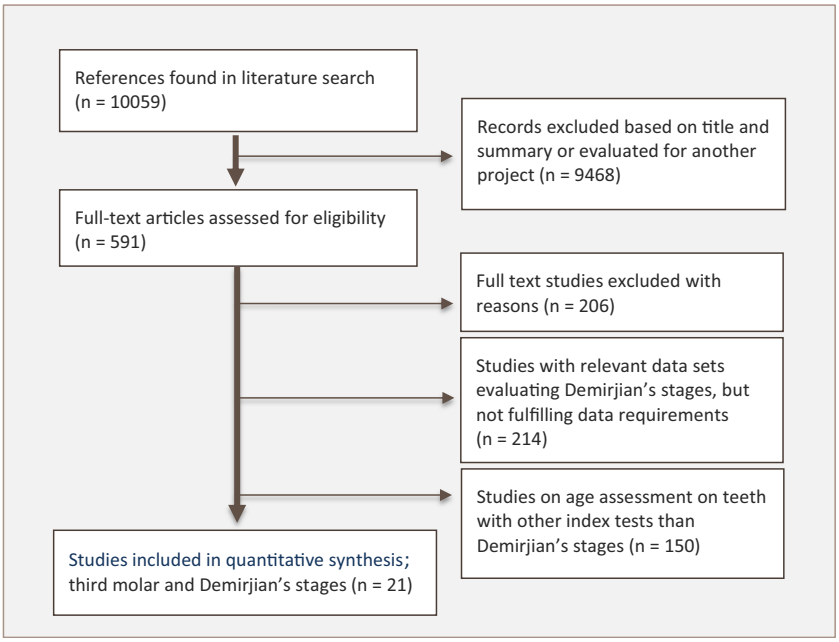

Fig. 1 Flow diagram of the systematic literature search (PRISMA flow diagram, [8])

truncation of the reference sample resulting in different age span. To demonstrate further the effect of the age structure of the included study population on the results, we presented mean age, SD, and 95% CI from three of the included studies together with the age structure of their reference sample.

Results

The literature search yielded 10,059 references (Fig. 1). Based on title and abstract, we excluded 9468 articles or considered these for the three parallel reviews. Figure 1 shows the literature search

Table 1 Characteristics of the included studies

First author, year (reference)	Country	Number (n)*	Male/female	Age (years)
Boonpitaksathit et al 2011 [14]	Great Britain	1223	453/770	12.6–24.9
Cavrić et al 2016 [15]	Botswana	1760	807/953	6–23
Elshehawi et al 2016 [16]	Malta	1593	742/851	4–26
Guo et al 2014 [18]	China	3512	1255/2257	11–24
Guo et al 2015 [17]	China	3212	1551/1661	5–25
Johan et al 2012 [19]	Malaysia	1080	540/540	14–25
Karadayi et al 2015 [20]	Turkey	784	379/405	8–23
Karataş et al 2013 [21]	Turkey	832	424/408	6–15
Lee et al 2009 [13]	South-Korea	3301	1610/1691	4–26
Li et al 2012 [22]	China	2078	989/1089	5–23
Lopez et al 2013 [23]	Brasil	659	280/379	15–22
Meinl et al 2007 [24]	Austria	610	275/335	12–24
Nur et al 2015 [25]	Turkey	1120	406/714	7–22
Olze et al 2006 [26]	South-Africa	595	474/121	10–26
Olze et al 2010 [27]	Canada	605	258/347	11–29
Olze et al 2012 [28]	South-Africa	553	437/116	10–26
Prieto et al 2005 [29]	Spain	1054	462/592	14–21
Qing et al 2014 [30]	China	2192	984/1208	8–25
Rougé-Maillart et al 2011 [31]	France	209	94/115	11–26
Zandi et al 2015 [32]	Iran	2536	982/1554	5–26
Zeng et al 2010 [33]	China	3100	1200/1900	4.1–26.9

*Number of included individuals

Table 2 Quality assessments of the included studies by QUADAS-2 checklist

First Author, Year	Quality assessment based on Quadas-2 domains				
	Selection bias				
	Patient selection	Age mimicry	Index test	Reference standard	Flow and timing
Boonpitaksathit 2011	?	?	?	+	+
Cavrić 2016*	?	+	?	+	+
Elshehawi 2016	+	?	+	+	+
Guo 2014	?	−	?	+	+
Guo 2015	+	−	+	+	+
Johan 2010**	?	−	?	+	+
Karadayi 2015	?	?	?	+	+
Karataş 2013	+	−	?	+	+
Lee 2009	?	+	?	+	+
Li 2012	?	+	+	+	+
Lopez 2013	?	−	+	+	+
Meinl 2007	+	−	?	+	+
Nur 2015	?	−	?	+	+
Olze 2006	?	−	?	+	?
Olze 2010	+	−	?	+	?
Olze 2012	?	−	+	+	?
Prieto 2005	?	?	?	+	+
Qing 2014	?	−	?	+	+
Rouge-Maillart 2011	+	?	?	+	−
Zandi 2015	+	−	+	+	+
Zeng 2010	+	?	?	+	+

+ Low risk, ? unclear risk, − high risk for systematic bias in the study

*Has an even number in each age group from 11 years and hence evaluated as non-biased by age mimicry. **Has a uniform age distribution, but a truncated age span (from 15 years) not appropriate to describe all analysed stages

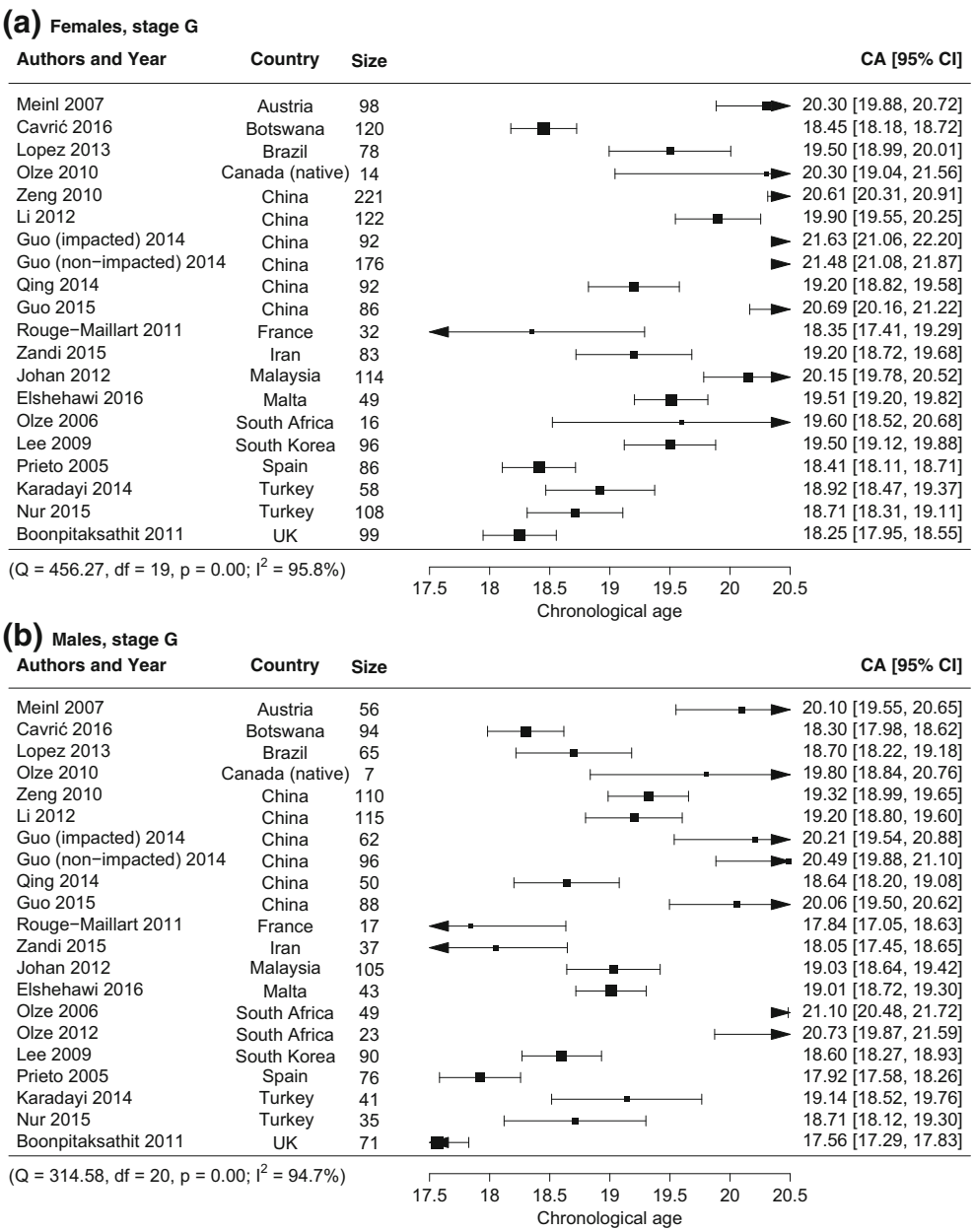

Fig. 2 Mean chronological age for Demirjian's stage G of the third molar 38 in each of the included studies. **a** Results for females. **b** Results for males. Results are given as mean age and 95% confidence interval [95% CI] within stage G for each study together with chi-squared statistic (Q), degrees of freedom of the chi-squared test (df), p value of the chi-squared test (p), and I-squared test for heterogeneity (I^2)

and selection of included studies. We examined 591 publications in full text, and 21 studies [13–33] met the inclusion criteria.

The included studies are presented in Table 1. Further description and quality assessment of the included studies are found in the technical report published in March 2017 [9]. In the present paper, three studies that were wrongly excluded in the technical report were included due to re-evaluation of all the publications according to inclusion criteria [15, 25, 30].

The included studies were published from 2005 to 2016. The study populations comprise both sexes and are from all continents, except Australia. The study sample size varied from 209 to 3512 individuals. There was also large variance in age span. The smallest age span was 7-year cohorts in the studies by Prieto (14–21 year) [29] and by Lopez (15–22 years) [23]. The widest ranged from 4.1 to 26.9 years (23-year cohort) in the study by Zeng [33]. All the included studies evaluated third molar stages by panoramic radiographs.

Quality assessment

A summary of our risk assessment based on the QUADAS-2 checklist is presented for each of the 21 studies in Table 2. Based on our judgment of the selected age span and number of individuals in each age group, we consider that the results in most of the studies can be influenced by age mimicry bias. Six of the studies did not present the number of individuals in each

CA	A	B	C	D	E	F	G	H	Total
9-10	21	8	4						33
10-11	22	20	13	1					56
11-12	5	19	37	2					63
12-13	2	5	41	8	1				57
13-14	1	4	25	21	5	1			57
14-15	1		11	20	10	5			47
15-16	1		2	13	13	27	5		61
16-17		1		12	18	24	9		64
17-18				5	11	22	18		56
18-19				1	7	15	25	6	54
19-20					3	3	17	32	55
20-21					1	1	7	47	56
21-22						1	5	51	57
22-23							4	51	55

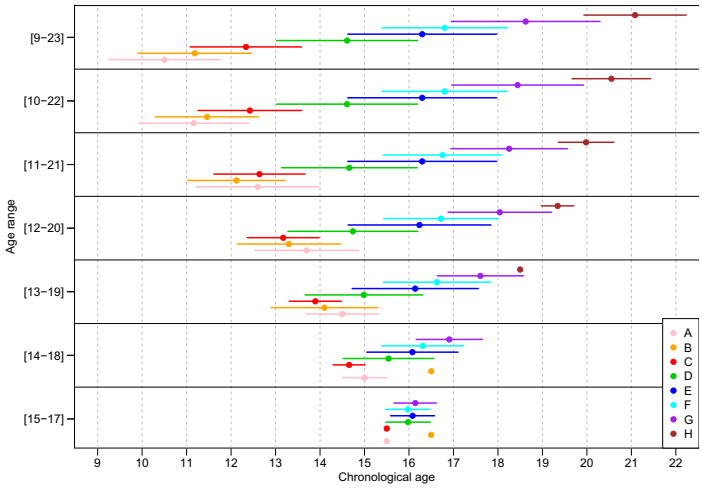

Fig. 3 Effect on truncation of the age span in the reference sample of a study. The table on the left displays a real distribution of individuals with different chronological ages (CA) considered to be in developmental stages A to H from Lee et al [13]. The figure to the right shows how the mean age and standard deviation (expressed as vertical line ± 1 SD from the mean) within each stage of development (colour-coded) changes according to truncation of the age span. The figure starts with participants from 9 to 23 years and gradually shows the age range down to the group 15–17 years

age group, and hence the risk of age mimicry is unclear. One study was judged as having high risk of bias in the domain patient flow and timing due to exclusion of individuals with closed apex (Demirjian's stage H) in all four wisdom teeth.

In Fig. 2, we present results of stage G for each study with heterogeneity test. These results are from the lower left third molar tooth 38 as this tooth is the most commonly considered. However, the technical report ([9], appendix 6) presents results for all third molars analysed in each study. Females and males are presented in separate graphs, A and B. Results from the other Demirjian's stages of 38 can be found in Supplementary material (stages A–H, except G). We observe large between-study variation in the mean age of the development stage G. For females, the mean age diverges from 18.25 years in the study by Boonpitaksathit et al [14] to 21.63 by Guo et al [18]. For males, the variation in the mean age for stage G ranges from 17.56 to 21.10 years in the included studies. The 95% CI of the means are wide for most stages and studies.

Due to the high risk of age mimicry bias in most of the included studies, we did not perform meta-analyses. This decision is supported by results of the heterogeneity tests and the

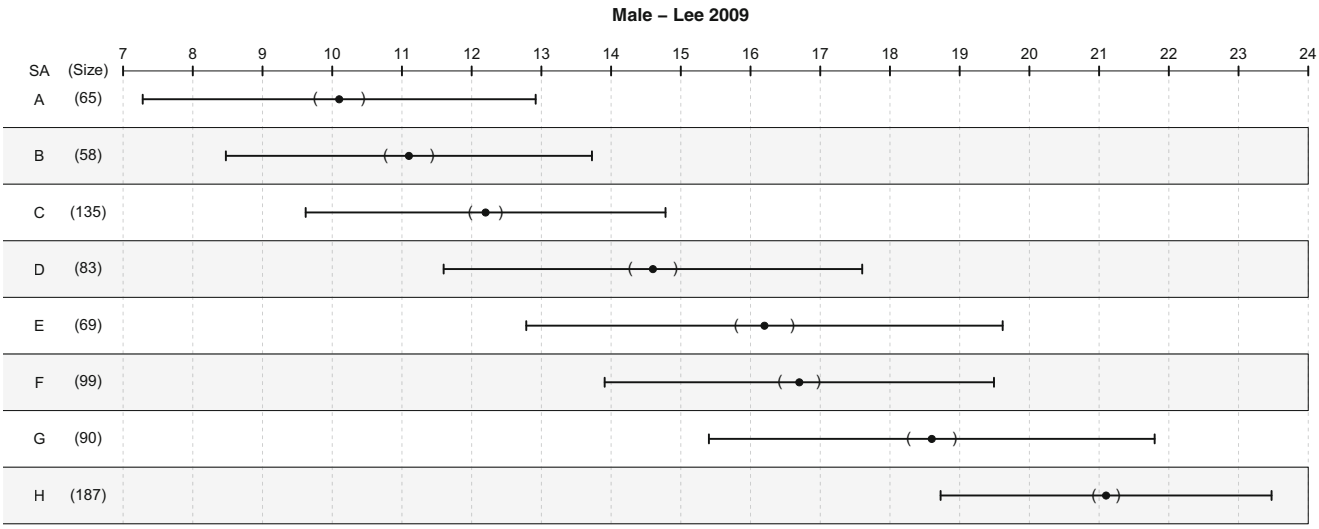

Fig. 4 Prediction intervals for Demirjian's third molar stages calculated from data by Lee et al [13]. **a** The mean chronological age (point) and the variation of chronological age (CA) for different stages (A–H) for males. Size gives number of individuals in each stage. The parenthesis presents the 95% confidence interval (95% CI), while the line provides a 95% prediction interval (95% PI)

I^2 index (Fig. 2 shows Q and I^2 for stage G). To illustrate the effect of age mimicry, we used data from one of the few studies with a nearly uniform age structure in their reference sample, and additionally present a frequency table of the included individuals with concurring stages [13]. Figure 3 exemplifies the effect of the included age range in the reference sample by using data from this study (Table 4, page 158, data for tooth 38 in males [13]). These results illustrate how the mean chronological age is drawn towards the age of the included test subjects and how a smaller age span reduces the standard deviation. Hence, the effect of truncation of the age span is increased bias and underestimated variation.

Figure 4 presents calculated 95% PI of age for the different stages based on data from the same study as in Fig. 3, Lee et al [13]. The 95% PI for each Demirjian's third molar stage vary from 4.7 years in stage H to 6.8 years in stage E. These results reveal large individual variation in age within third molar development stages. These 95% PIs also illustrate how reference data can be used to describe the age variation within each Demirjian's stage of tooth development.

To elucidate the effect of age mimicry further, we present study results superimposed on the age distribution of the reference sample for males from three of our included studies (Fig. 5): one study with uniform age distribution and a wide age span [13], another study with a wide age span and uneven sized age groups [17], and the last study with a narrow age span and different numbers of individuals in each age group [23].

Discussion

In this systematic review, we summarise the literature estimating the mean age of Demirjian's development stages for the third molar among adolescents and young adults. Twenty-one studies fulfilled our inclusion criteria and presented mean

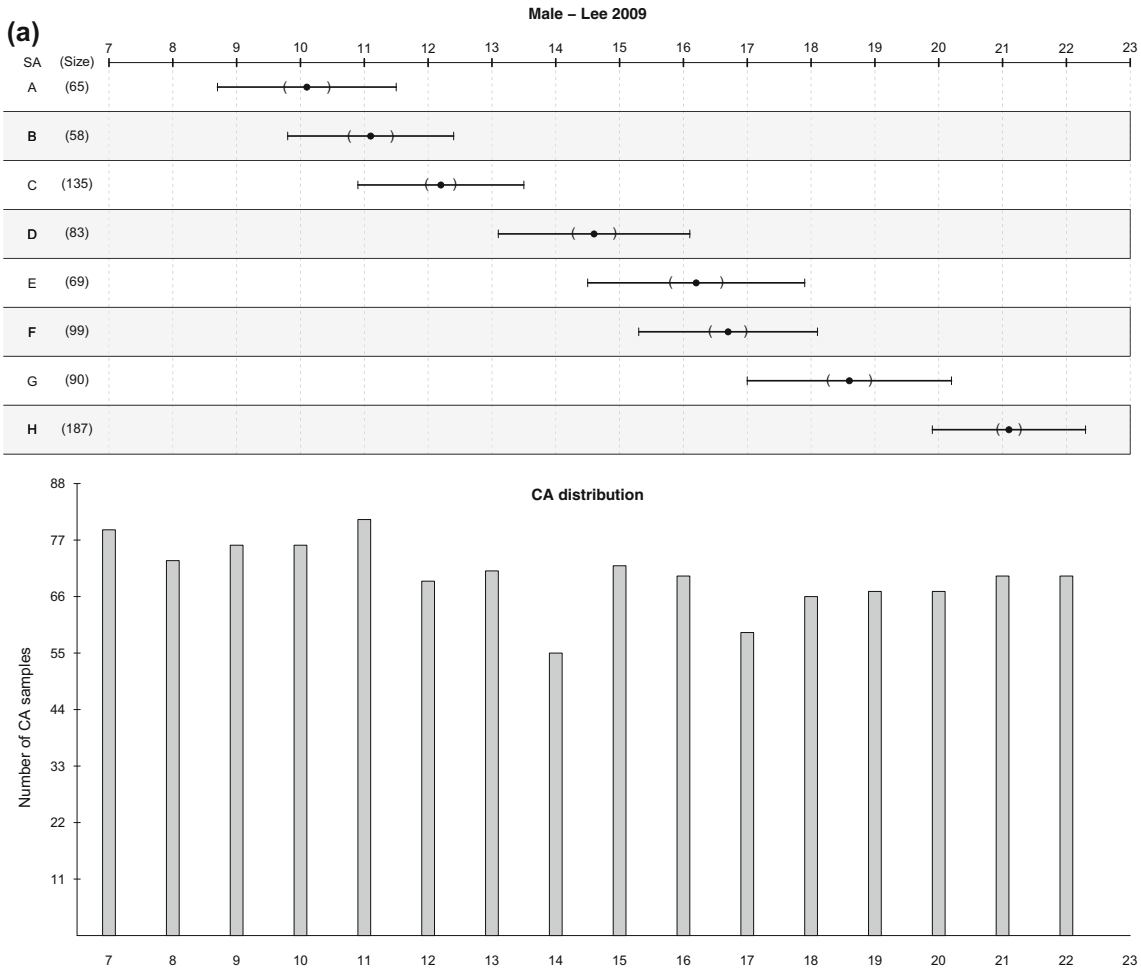

Fig. 5 Results for males from three included studies together with the age distribution of the reference sample. **a** Male mean age and variation of each Demirjian's third molar stage from Lee et al [13] with chronological age (CA) distribution of the reference sample. **b** Male mean age and variation of each Demirjian's third molar stage from Guo et al [17] with CA distribution of the reference sample. **c** Male mean age and variation of each Demirjian's third molar stage from Lopez et al [23] with CA distribution of the reference sample. The filled circles show mean age and the line is one SD (95% confidence interval in parenthesis). The bars show number of individuals in each age group

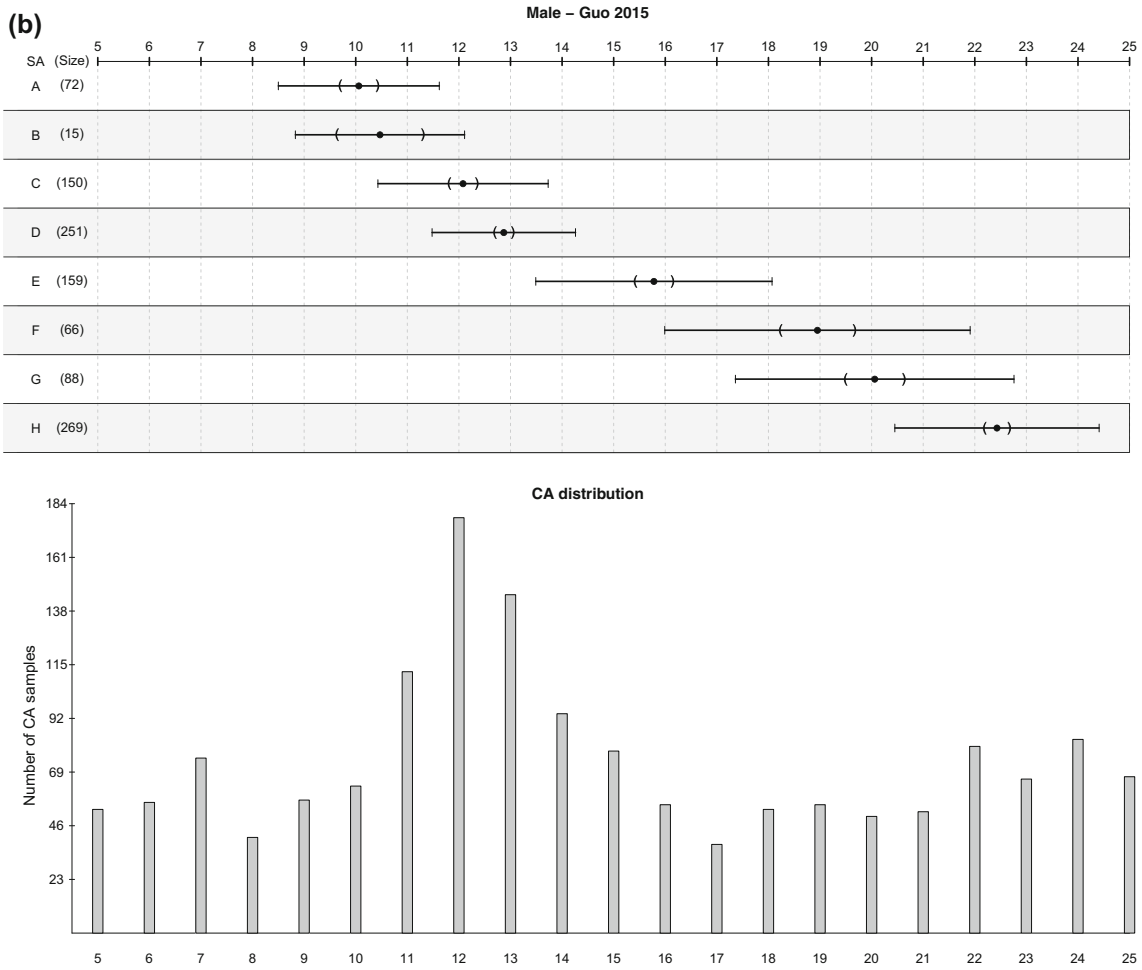

Fig. 5 (continued)

chronological age with variance and number of individuals in each stage for all or some of Demirjian's stages A–H.

Our main finding is that a majority of these studies are highly influenced by age mimicry bias, a selection bias caused by the age composition of their reference sample. The bias arises when studies include a non-uniform number of individuals in the different age groups studied and/or the age span is inappropriate to describe all development stages analysed. Furthermore, several studies have not described the age structure of the reference sample, thereby making it impossible to assess if the results are reliable. If a study aims to describe how mean chronological age of a population is directly distributed within developmental stages, it is essential to include an equal number of individuals in each age group. Likewise, the age range in such a study should be broad enough to cover all probable ages for the described stages. This is critical in order to make the studies comparable and applicable as reference data for further analysis.

Age mimicry bias was first described in 1982 by paleodemographers assessing the age of skeletons [10]. Several guides and publications on age assessment in living individuals have also stressed the risk of age mimicry bias [34–36]. In spite of this awareness, even recently published studies on third molar age assessment have not considered this factor in the study design. Moreover, several papers have discussed possible causes of variations between studies without taking this bias into account. Often, such variations have been interpreted as ethnic differences. As shown in the results, the mean age for stage G among boys varies from 17.56 to 21.10 in the studies. This may be due to factors such as biological or environmental (including nutritional) variations, but can also very likely be attributable to inadequate sample size in each stage (e.g., down to 7 individuals for studies on female stage G, see Fig. 2a) and age mimicry bias.

The age structure of the reference sample will affect the statistics of different stages at varying degrees due to the composition of the included individuals. Studies judged as biased in this review may have some stages more affected by age mimicry than other stages. However, evaluating the risk of bias for each stage is a complex analysis and beyond our current scope.

Another important factor is that the studies present standard deviation or confidence intervals for age in each stage. Due to the natural biological variation, it is important to present the age variation of the population of each tooth stage in a predictive way. Consequently, we have calculated 95% PI based on

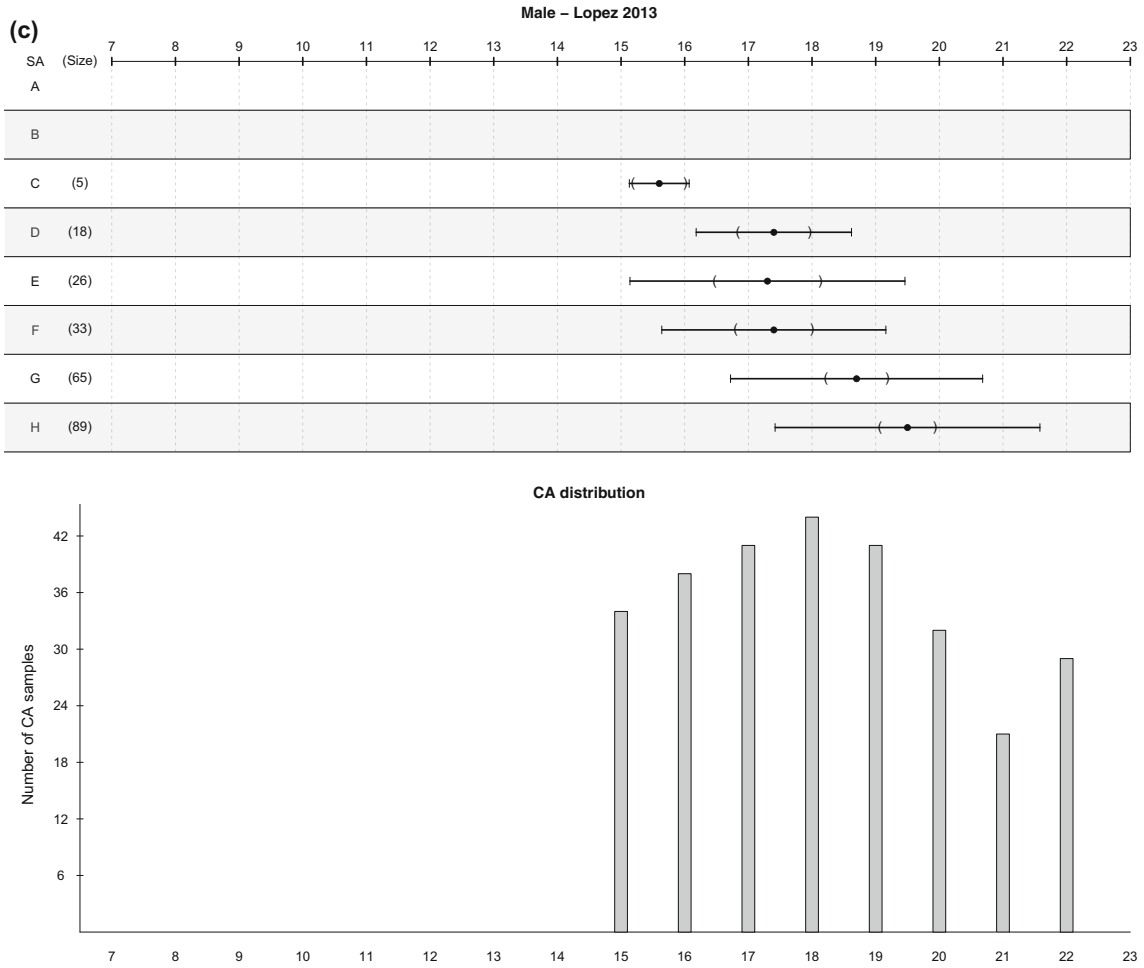

Fig. 5 (continued)

data from one of the studies with an adequate study design, Lee et al [13]. Our calculations show relatively large natural variation in age within each stage, up to nearly 7 years. However, the PI calculation assumes normal distribution of age within each stage—an assumption that may not always be valid for third molar development [37].

Notably, there is a particular problem with stage H as this is the final development stage. It is also an important stage in order to determine whether a person is younger or older than 18 years. The upper age of the enrolled participants in a study will strongly influence the observed results—a higher included upper age will result in higher mean age and wider standard deviation for stage H. In this systematic review, the study with the highest mean age for stage H (23.2 years) also included the oldest individuals (up to 29 years) [27], whereas the study by Prieto, that included individuals only up to 21 years, reports mean age for stage H to be 19.7 years. Other sources of heterogeneity between studies also occur, including the example of Rougé-Maillart et al [31] that excluded individuals with all third molars matured and thereby got a lower mean age for stage H. Several approaches to avoid the problem of stage H have been suggested, for instance to set an age limit of where the anterior stage G stops [13, 38]. Another method used is by giving the age where 50% of the individuals have entered stage H [27, 39].

In recent years, a Bayesian approach to age estimation has gained significant interest [11, 40–45]. With chronological age and corresponding stage for each individual, it is possible to control the effect of age mimicry by performing a statistical analysis using Bayes theorem. To make use of studies already conducted and avoiding age mimicry (i.e., indirectly applying Bayes theorem with a uniform age distribution as a prior for age), we recommend collecting individual data from already published studies as a time- and cost-efficient approach. A joint effort will result in a reference data set including a high number of individuals from many populations around the world. Calculated prediction intervals based on such analyses will give an improved base for age assessment for judicial purposes. However, the question relating the representativeness of the included population in such a model for a future tested individual still remains. Hence, there is still a need for studies of new populations (designed to avoid age mimicry).

Conclusion

Variation observed between studies reporting mean chronological age of Demirjian's stages for wisdom teeth has often been interpreted as differences in tooth development between populations and ethnicities. However, we consider the effect of age mimicry to be a dominant source of bias in these studies and conclude that the scientific evidence is insufficient to assess whether such differences exist. Based on one of the few studies avoiding age mimicry, we calculated 95% PI for chronological age in each development stage. We found that the age variation within the different Demirjian's development stages ranged from 4.7 to 6.8 years, reflecting large individual variation in third molar mineralisation.

Acknowledgements The authors thank Marit Johansen for peer review of the literature search strategy.

Funding The authors state that this work has not received any funding.

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is the last author, Gunn Elisabeth Vist, Division for Health Services, Norwegian Institute of Public Health, Norway.

Conflict of interest The authors declare that they have no conflict of interest.

Statistics and biometry Two of the authors have significant statistical expertise.

Informed consent Written informed consent was not required for this study because it is a systematic review of published studies.

Ethical approval Institutional Review Board approval was not required because it is a systematic review of published studies.

Study subjects or cohorts overlap Some study subjects or cohorts have been previously reported in a technical report published in Norwegian by the Norwegian Institute of Public Health (PubMed: https://www.ncbi.nlm.nih.gov/pubmed/29553688).

Compared to the technical report in Norwegian, the submitted manuscript has been rewritten and updated with three more included studies.

Methodology
• Systematic review

References

1. UNICEF (2013) Every child's birth right: inequities and trends in birth registration. UNICEF, New York
2. EASO (2018) Practical guide on age asessment. Available from: https://www.easo.europa.eu/sites/default/files/easo-practical-guide-qualification-for-international-protection-2018.pdf. European Asylum Support Office
3. Demirjian A, Goldstein H, Tanner JM (1973) A new system of dental age assessment. Hum Biol 45:211–227
4. Moorrees CFA, Fanning EA, Hunt EE Jr (1963) Age variation of formation stages for ten permanent teeth. J Dent Res 42:1490–1502
5. Mincer HH, Harris EF, Berryman HE (1993) The A.B.F.O. study of third molar development and its use as an estimator of chronological age. J Forensic Sci 38:379–390
6. Dahlberg PS, Mosdøl A, Ding Y et al (2018) A systematic review of the agreement between chronological age and skeletal age based on the Greulich and Pyle atlas. Eur Radiol. https://doi.org/10.1007/s00330-018-5718-2
7. Higgins JPT, Green S (2011) Cochrane handbook for systematic reviews of interventions Version 5.1.0 [updated March 2011]. The Cochrane Collaboration
8. Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 339:b2535
9. Rolseth V, Mosdøl A, Dahlberg PS et al (2017) Demirjians utviklingsstadier på visdomstenner for estimering av kronologisk alder: en systematisk oversikt (Demirjian's Development Stages on Wisdom Teeth for Estimation of Chronological Age: A Systematic Review). Knowledge Centre for the Health Services at The Norwegian Institute of Public Health (NIPH), Oslo, Norway. Available from: https://www.fhi.no/en/publ/2017/demirjians-utviklingsstadier-pa-visdomstenner-for-estimering-av-kronologisk/
10. Bocquet-Appel JP, Masset C (1982) Farewell to paleodemography. J Hum Evol 11:321–333
11. Boldsen JL, Milner GR, Konigsberg LW, Wood JW (2002) Transition analysis: a new method for estimating age from skeletons. In: Hoppa RD, Vaupel JW (eds) Paleodemography: age distributions from skeletal samples. (Cambridge Studies in Biological and Evolutionary Anthropology). Cambridge University Press, Cambridge, pp 73–106
12. Chaumoitre K, Saliba-Serre B, Adalian P, Signoli M, Leonetti G, Panuel M (2017) Forensic use of the Greulich and Pyle atlas: prediction intervals and relevance. Eur Radiol 27:1032–1043
13. Lee SH, Lee JY, Park HK, Kim YK (2009) Development of third molars in Korean juveniles and adolescents. Forensic Sci Int 188:107–111
14. Boonpitaksathit T, Hunt N, Roberts GJ, Petrie A, Lucas VS (2011) Dental age assessment of adolescents and emerging adults in United Kingdom Caucasians using censored data for stage H of third molar roots. Eur J Orthod 33:503–508
15. Cavrić J, Vodanović M, Marušić A, Galić I (2016) Time of mineralisation of permanent teeth in children and adolescents in Gaborone, Botswana. Ann Anat 203:24–32
16. Elshehawi W, Alsaffar H, Roberts G, Lucas V, McDonald F, Camilleri S (2016) Dental age assessment of Maltese children and adolescents. Development of a reference dataset and comparison with a United Kingdom Caucasian reference dataset. J Forensic Leg Med 39:27–33
17. Guo YC, Lin XW, Zhang WT et al (2015) Chronology of third molar mineralisation in a northern Chinese population. Rechtsmedizin 25:34–39
18. Guo YC, Yan CX, Lin XW et al (2014) The influence of impaction to the third molar mineralisation in northwestern Chinese population. Int J Legal Med 128:659–665
19. Johan NA, Khamis MF, Abdul Jamal NS, Ahmad B, Mahanani ES (2012) The variability of lower third molar development in Northeast Malaysian population with application to age estimation. J Forensic Odontostomatol 30:45–54
20. Karadayi B, Kaya A, Afsin H, Ozaslan A, Çetin G (2015) The usage of third molars to determine legally relevant age thresholds in Turkey. Aust J Forensic Sci 47:275–282

21. Karataş OH, Öztürk F, Dedeoğlu N, Çolak C, Altun O (2013) Radiographic evaluation of third-molar development in relation to the chronological age of Turkish children in the southwest Eastern Anatolia region. Forensic Sci Int 232:238.e231–238.e235
22. Li G, Ren J, Zhao S et al (2012) Dental age estimation from the developmental stage of the third molars in western Chinese population. Forensic Sci Int 219:158–164
23. Lopez TT, Arruda CP, Rocha M, Rosin AS, Michel-Crosato E, Biazevic MG (2013) Estimating ages by third molars: stages of development in Brazilian young adults. J Forensic Leg Med 20: 412–418
24. Meinl A, Tangl S, Pernicka E, Fenes C, Watzek G (2007) On the applicability of secondary dentin formation to radiological age estimation in young adults. J Forensic Sci 52:438–441
25. Nur B, Altunsoy M, Akkemik Ö, Ok E, Evcil MS (2015) Third-molar mineralisation and eruption correlated to chronologic age in Turkish children and adolescents. Aust J Forensic Sci 47:313–321
26. Olze A, van Niekerk P, Schmidt S et al (2006) Studies on the progress of third-molar mineralisation in a Black African population. Homo 57:209–217
27. Olze A, Pynn BR, Kraul V et al (2010) Studies on the chronology of third molar mineralisation in First Nations people of Canada. Int J Legal Med 124:433–437
28. Olze A, van Niekerk P, Schulz R, Ribbecke S, Schmeling A (2012) The influence of impaction on the rate of third molar mineralisation in male black Africans. Int J Legal Med 126:869–874
29. Prieto JL, Barbería E, Ortega R, Magaña C (2005) Evaluation of chronological age based on third molar development in the Spanish population. Int J Legal Med 119:349–354
30. Qing M, Qiu L, Gao Z, Bhandari K (2014) The chronological age estimation of third molar mineralisation of Han population in southwestern China. J Forensic Leg Med 24:24–27
31. Rougé-Maillart C, Franco A, Franco T, Jousset N (2011) Estimation of the age of 15-25 year-olds using Dermirjian's dental technique. Study of a population from the West, France. Revue de Medecine Legale 2:117–124
32. Zandi M, Shokri A, Malekzadeh H, Amini P, Shafiey P (2015) Evaluation of third molar development and its relation to chronological age: a panoramic radiographic study. Oral Maxillofac Surg 19:183–189
33. Zeng DL, Wu ZL, Cui MY (2010) Chronological age estimation of third molar mineralisation of Han in southern China. Int J Legal Med 124:119–123
34. Schmeling A, Garamendi PM, Prieto JL and Landa MI (2011) Forensic age estimation in unaccompanied minors and young living adults, forensic medicine - from old problems to new challenges. Prof. Duarte Nuno Vieira (Ed.), InTech. https://doi.org/10.5772/19261. Available from: https://www.intechopen.com/books/forensic-medicine-from-old-problems-to-new-challenges/forensic-age-estimation-in-unaccompanied-minors-and-young-living-adults
35. Liversidge HM, Smith BH, Maber M (2010) Bias and accuracy of age estimation using developing teeth in 946 children. Am J Phys Anthropol 143:545–554
36. Liversidge HM (2012) The assessment and interpretation of Demirjian, Goldstein and Tanner's dental maturity. Ann Hum Biol 39:412–431
37. Bleka Ø, Wisløff T, Dahlberg PS, Rolseth V, Egeland T (2018) Advancing estimation of chronological age by utilizing available evidence based on two radiographical methods. Int J Legal Med. https://doi.org/10.1007/s00414-018-1848-y
38. Roberts GJ, McDonald F, Andiappan M, Lucas VS (2015) Dental age estimation (DAE): data management for tooth development stages including the third molar. Appropriate censoring of stage H, the final stage of tooth development. J Forensic Leg Med 36: 177–184
39. Knell B, Ruhstaller P, Prieels F, Schmeling A (2009) Dental age diagnostics by means of radiographical evaluation of the growth stages of lower wisdom teeth. Int J Legal Med 123:465
40. Konigsberg LW, Herrmann NP, Wescott DJ, Kimmerle EH (2008) Estimation and evidence in forensic anthropology: age-at-death. J Forensic Sci 53:541–557
41. Thevissen PW, Fieuws S, Willems G (2010) Human dental age estimation using third molar developmental stages: does a Bayesian approach outperform regression models to discriminate between juveniles and adults? Int J Legal Med 124:35–42
42. Sironi E, Vuille J, Morling N, Taroni F (2017) On the Bayesian approach to forensic age estimation of living individuals. Forensic Sci Int. https://doi.org/10.1016/j.forsciint.2017.11.007
43. Sironi E, Pinchi V, Pradella F, Focardi M, Bozza S, Taroni F (2018) Bayesian networks of age estimation and classification based on dental evidence: a study on the third molar mineralisation. J Forensic Leg Med 55:23–32
44. Liversidge HM, Peariasamy K, Folayan MO et al (2017) A radiographic study of the mandibular third molar root development in different ethnic groups. J Forensic Odontostomatol 2:97–108
45. Tangmose S, Thevissen P, Lynnerup N, Willems G, Boldsen J (2015) Age estimation in the living: transition analysis on developing third molars. Forensic Sci Int 257:512.e511–512.e517