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Age estimation: The state of the art in relation to the specific demands of forensic practise

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Abstract Age estimation in cadavers, human remains and living individuals may clarify issues with significant legal and social ramifications for individuals as well as for the community. In such cases methods for estimating age should fulfil the following specific demands: (1) they must have been presented to the scientific community, as a rule by publication in peer-reviewed journals, (2) clear information concerning accuracy of age estimation by the method should be available, (3) the methods need to be sufficiently accurate and (4) in cases of age estimation in living individuals principles of medical ethics and legal regulations have to be considered. We have identified and summarized the methods that essentially fulfil these specific demands. In childhood and adolescence morphological methods based on the radiological examination of dental and skeletal development are to be recommended. In adulthood, the accuracy of most morphological methods is much reduced. Here a biochemical method based on aspartic acid racemization in dentine provides the most accurate estimates of age, followed by special morphological dental and skeletal methods. The choice of method has to take account of the individual circumstances of each case. Most methods require either the consultation of specialised and trained scientists or an adequate calibration by the "user". Very few attempts have been made to find common standardisation, calibration and evaluation procedures or to develop means of quality assurance for methods of age estimation. Efforts in these directions are necessary to guarantee quality standards and adequate answers to the important legal and social issue of age estimation in forensic medicine.

Key words Age estimation · Forensic practise · Demands · State of the art

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The increasing need for accurate methods for age estimation in forensic practise

The need for accurate techniques for age estimation has never been greater. In the last decade the need has increased for two main reasons, both related to current sociopolitical developments. The first is the increasing number of unidentified cadavers and human remains, the second a rise in cases requiring age estimation in living individuals with no valid proof of date of birth. These developments have greatly underlined the importance of ageing both human remains and living individuals.

There are currently no comprehensive statistics detailing the number of unidentified cadavers and human remains within the European community. The following data were compiled for Germany (unpublished data provided by Bundeskriminalamt Wiesbaden): about 50–70 cadavers remain unidentified every year and the trend is upward. At present (November 1998), a total of 1214 unidentified cadavers and 6076 missing persons are registered by the German authorities. Although no national Italian statistics exist, the city of Milan has registered 91 cases of unidentified cadavers and human remains since 1995 and registers approximately 30 new missing persons every month (unpublished data provided by the Istituto di Medicina Legale, Universita di Milano and by Questura di Milano). It can be assumed that other European countries are confronted with similar numbers of unidentified cadavers. The problem appears to be growing because of the increase in (both legal and illegal) im-

migration and flow of individuals into and across the European Union.

The implications of a "lack of identification" of a cadaver are not to be underestimated. Appropriate identification is important not only for administrative and ethical reasons, but also because of serious legal consequences. In civil law, the death of a person (which can only be proclaimed following correct identification of the deceased) changes the civil and juridical status not only of the deceased but also of the relatives. Death has major economic and financial ramifications for the relatives arising from issues of inheritance and insurance. In criminal law, lack of identification seriously hampers murder enquiries. Finally, false or unidentified cadavers offer an opportunity to illegally obtain identity documents and thereby switch identity.

When attempting to match unidentified remains against hundreds of missing individuals, age is a primary factor crucial for preliminary screening procedures. Age estimation is therefore one of the standard requests made by police and judicial authorities upon the discovery of a dead body.

Estimation of age is also becoming crucial in living individuals. Many European countries have registered an increase in the influx of individuals lacking valid identity documents (e.g. refugees, illegal immigrants). In Italy, this development has resulted in an increase in the prison population of foreign juvenile delinquents with no valid documents from a total of 7000 in 1991 to over 13000 in 1997 (data quoted in Dossier Statistico della Caritas di Roma 1997 and by the Ministery degli Interni and ISTAT [Italian statistical organ]). Knowledge of the age of living individuals without valid documents may be required to clarify legal questions concerning the imputability of juvenile or young adult delinquents, pension claims of older individuals or requests for political asylum [80].

The demands for methods of age estimation are dependent on the circumstances of individual cases. In many cases an approximate age estimation by a trained and experienced person based on the anthropological/dental status, which can be performed quickly and immediately, is sufficient, for example for confirmation of the identity of a deceased in connection with other findings. However, in other cases age estimation has to be as accurate as possible – for example, if the identity of a victim of a murder case is unclear or if legal questions concerning the imputability of young delinquents have to be clarified. In such cases age estimation may play a central role in the clarification of questions which have a major legal and/or social impact for the individual as well as for the community; this is the peculiarity of age estimation in forensic practice. In such a framework, methods for age estimation have to fulfil specific demands which are outlined below.

Specific demands for methods of age estimation in forensic practice

A. The methods must be transparent and provable, the underlying data must have been presented to the scientific community, as a rule by publication in peer-reviewed journals. The published papers should contain all relevant details of the method including material and statistics to make the method transparent and to enable verification by other scientists. Vague or ambiguous methods cannot be applied or evaluated and should not be considered suitable to solve forensic questions of legal or social significance.

B. Clear information concerning the accuracy of age estimation by the method should be available. Accuracy must have been tested by using valid statistical procedures and described by clearly defined terms. Indeed the lack of adequate statistical processing is one of the most important limitations to the practical application of methods for age estimation [88].

C. The methods need to be accurate enough to fulfil the specific demands of the single case to solve the underlying questions. With good reason Rösing and Kvaal [88] stated that "methods with a standard error of regression of more than five or seven years are not suitable for routine forensic application". What does a standard error of 7 years mean? It means that 95% confidence intervals of about $\pm$ 14 years or even more [20] have to be considered in age estimation. It may be a waste of time and money to apply less accurate methods since their results may not improve the (non–scientific) estimation of an "apparent age" often done by the investigating authorities (mainly based on facial parameters), for example in living individuals and fresh cadavers.

D. In cases of age estimation in living individuals principles of medical ethics and legal regulations have to be considered, especially if medical intervention is involved [80].

The question arises: Which methods can fulfil these specific demands?

Numerous papers concerning age estimation have been summarized in different review articles and books [34, 42, 53, 80, 88, 105, 108, 110, 113]. Most reviews give indications as to the "preferred" methods according to the author, but usually no statistically founded reasons for such a choice are given. Not infrequently methods which are commonly considered inaccurate (such as ectocranial suture closure) are still recommended. The special demands listed above (A-D) have rarely been considered and then only by a minority of authors (e.g. by Rösing and Kvaal [88]).

This may be mainly ascribed to the lack of consistent data concerning the accuracy of methods for age estimation. Studies that test various methods in an independent material are rare and as a rule limited to special fields (e.g. dental and skeletal methods) [4, 6, 15, 29, 33, 46, 72, 89, 90, 99]. A comparison of different methods with regard to their accuracy based on published original data can be performed only with severe limitations. The methods have been developed on samples of differing or unknown size and age structure. Different statistical procedures have been applied. In many cases there is a lack of details regarding the procedures used and in some cases there are even statistical inconsistencies [59]. Many authors present "errors", but the term is rarely well defined. If the rela-

tionship between age and a possible age indicator is tested by regression analysis, the published regression formulas mostly include the sample standard error of estimate (for definition and meaning of this term see [20]). This standard error (hereafter termed SEE) has been frequently used as a measure of the accuracy of the method, although this approach has been rightly criticised [3, 20].

However, the published data can be used to identify a group of methods which basically fulfil the demands (A-D) listed above, if they are applied properly by trained personnel.

The following overview is an attempt to summarise relevant information about these methods and to give recommendations for their application. The selection of the included methods was performed according to the demands listed above (A-D). Methods were included, if they were published with all relevant data in peer-reviewed journals and if their accuracy was not too poor (SEE below ± 7 years) or doubtful (due to an insufficient material or a lack of statistics). To keep information condensed, the included methods will not be described in detail (such details can be obtained by consulting the cited literature). We have attempted to restrict cited literature to original, basic and/or recent literature which we believe will be of greatest value.

Methods that can be recommended under consideration of the specific demands of forensic practise. An overview

In childhood, age estimation can be performed very accurately using morphological (developmental) methods, because a great number of age-dependent morphological features (especially of the dental and skeletal system) can be evaluated. At the end of skeletal growth and development, only a few age-dependent features (e.g. the development of the third molars and of bones of the wrist and hand) remain to be used for age estimation by morphological methods, resulting in a progressive decrease in accuracy with increasing age. In adulthood, the accuracy of most morphological methods is poor; in this age group a biochemical method (based on aspartic acid racemization in dentin) offers the most accurate results.

Because different age groups demand the application of different methods, the following overview is divided in two parts presented in two tables: "Recommended methods" for age estimation (1) in childhood and adolescence (Table 1) and (2) in adulthood (Tables 2 A and 2B). The Tables contain information on the applicability of the methods (situations and age ranges in which they should be applied), the published standard errors (SEE) and correlation coefficients (r) as descriptors of the "accuracy" of the methods and list the relevant literature. They also include critical remarks that especially focus on the question of whether the methods have been tested for the influences of sex and race. The intention of the columns "SEE" and "r" is not to present every published value for these statistics. For the different groups of methods "cumulative" ranges for SEE and r are given to describe the order of accuracy; details can be obtained from the cited literature. A certain degree of simplification and generalisation had to be taken into account to enable comparison; this will not lead to misapplication because the application of a specific method requires calibration by each "user" (see "final remarks" below).

Guidelines for special cases

Fresh cadavers

All methods listed in the Tables are applicable.

In childhood radiological methods based on the examination of dental and/or skeletal development (I and II in Table 1) will provide good results.

Table 1 Recommended methods for age determination in childhood and adolescence: situations and age ranges (in years [y]) in which they should be applied, published standard errors (SEE) and correlation coefficients (r) as indicators for the "accuracy" of the methods, critical remarks and relevant literature

Methods	Recommended…		SEE	r	Remarks	Literature
	for	in age ranges				
I. Radiological examination of dental development						
Ia. …of all tooth types	Cadavers, human remains, historic and archaeological cases, living individuals	0–c.14y	± 0.5–1y	0.50–0.88	With increasing age less accurate. Sex and race influence the tooth development	13, 14, 27, 28, 29, 55, 71, 90, 95
Ib. …of the third molars	as Ia	c.14–21y	± 1–2.5y	0.32–0.85	as Ia	16, 44, 46, 54, 69, 104
II. Radiological examination of skeletal development	Cadavers, human remains, historic and archaeological cases, living individuals	0–c.18y	± 0.5–2y	0.64–0.88	With increasing age less accurate. Sex, race and socio-economic environment influence the skeletal development	16, 22, 46, 57, 68, 77, 87, 102, 109

Table 2A Recommended methods for age estimation in adults I (dental methods): situations and age ranges (in years [y]) in which they should be applied, published standard errors (SEE) and correlation coefficients (r) as indicators for the "accuracy" of the methods, critical remarks and relevant literature

Methods	Recommended…		SEE	r	Remarks	Literature
	for	in age ranges				
III. Evaluation of dental morphology including histological features						
IIIa. Combined methods (e.g. "Gustafson method" and its modifications)	Cadavers and human remains, living individuals (as far as an extracted tooth is available)	All ages with permanent teeth	± 5–12y	0.57–0.91	Influence of sex, race and socio-economic standards unclear. Doubts on applicability in historical cases	5, 25, 26, 52, 59, 61, 88, 93, 94, 110, 111
IIIb. Methods based on cementum annulation	as IIIa, also on historical and archaeological cases	as IIIa	± 4–10y	0.78–0.93	With increasing age less less accurate. Dental diseases influence results. Influence of sex, race and socio-economic standards unclear	10, 12, 24, 49, 56, 88, 96
IV. Determination of aspartic acid racemization in dentine	Cadavers and human remains, living individuals (as far as an extracted tooth or a biopsy sample is available)	All ages with availibility of teeth	± 1.5–4y	0.97–0.99	Should not be applied in burnt remains. In historical cases only applicable in cases with extreme low post-mortem temperatures. Influence of sex and race remains to be tested, albeit it is not to be expected	18, 31, 70, 73–76, 82, 83, 85, 88

Table 2B Recommended methods for age estimation in adults II (skeletal methods): situations and age ranges (in years [y]) in which they should be applied, published standard errors (SEE) and correlation coefficients (r) as indicators for the "accuracy" of the methods, critical remarks and relevant literature

Methods	Recommended…		SEE	r	Remarks	Literature
	for	in age ranges				
V. Evaluation of skeletal morphology						
Va. Macroscopic features …						
…Pubic symphysis	Cadavers and human remains, historic and archaeological cases	< 40y	± 2–4y at best	0.85 at best	With increasing age less accurate. Sex, race and possibly socio-economic environment influence morphology	8, 19, 30, 38, 39, 64, 66, 92
…Ribs	as pubic symphysis	< 40y	similar to pubic symphysis		as pubic symphysis	15, 35–37
Vb. Evaluation of bone histology	as Va	all ages	± 5–12y	0.69–0.90	Possible sex difference in histologic features should be considered. Influence of race unclear. Applicable to burnt remains	1, 6, 7, 17, 40, 41, 43, 97–101, 103, 106, 112
Vc. Multifactorial methods considering several features	as Va	all ages	c. ± 4.5y at best	0.72–0.9	as Va. and Vb., depending on included features, with increasing age less accurate	4, 58, 65, 89

In adolescence the accuracy of age estimation by these radiological methods decreases, nevertheless they are also to be regarded as "most accurate methods" in this age group.

In adults, estimation of aspartic acid racemization in dentine (IV in Table 2A) is to be recommended, if teeth are available. Its accuracy and reproducibility are higher than those of conventional morphological methods (III and V in Tables 2 A and 2B). If teeth are not available macromorphological and histomorphometrical skeletal features have to be used (V in Table 2B); to overcome the problem of outliers arising from possible biological variation of single skeletal features, "multiple methods of age estimation based on a variety of age-related structures should be used on an individual" [33]. In younger adults additional methods (e.g. evaluation of pubic symphyseal and rib morphology, see Table 2B) can also be applied resulting in more accurate age estimates than in older adults.

Putrefied remains, skeletons

Basically the same procedures as for fresh cadavers can be recommended.

All macroscopic and microscopic morphologic methods can be applied (I and II in Table 1, III and V in Tables 2 A and 2B). Doubts exist as to whether microscopical methods on teeth (III in Table 2A) can be applied on skeletal material which has been buried for several decades (see historical cases).

The biochemical method based on aspartic acid racemization (IV in Table 2A) can be successfully applied as long as the remains are not burnt and the postmortem interval does not exceed a few decades (see burnt remains and historical cases).

Burnt remains

The applicability of the methods listed in the Tables depends on the extent of the destruction of the burnt body. Even in cases with extensive destruction of the body, the teeth are frequently preserved, especially the molars. Methods based on the combined morphological evaluation of dental features (IIIa in Table 2A) are only applicable if the tooth is entirely preserved. Even if the tooth is only charred, they cannot be applied, since parameters such as transparency cannot be observed. Methods based on cementum annulation (IIIb in Table 2A) are more likely to remain applicable [23].

Some body parts such as the pubic symphysis are often well preserved even in burnt bodies, because of their anatomical position, whereas bones easily exposed to the effect of fire, such as the ribs, are usually destroyed. Thus the applicability of methods based on the evaluation of skeletal macromorphological features (Va in Table 2B) may be limited.

The only method which is systematically applicable even on charred diaphyseal remains is bone histology (Vb in Table 2B), since osteons are usually distinguishable in burnt bone and bone shrinkage does not seem to greatly affect age estimation [7].

The biochemical methods based upon aspartic acid racemisation (IV in Table 2A) should be avoided because the racemization process is highly temperature dependent [11] and heat may induce unpredictable post mortem increases of aspartic acid racemization [107] if the proteins used are not entirely destroyed.

Body parts

If the body parts available do not allow the application of the methods summarised in the Tables, novel methods under development may become the "most accurate methods".

Since aspartic acid exhibits an age–dependent racemization in numerous permanent proteins of various tissues, the possibility of a biochemical age estimation can be considered; an age-dependent increase of D-aspartic acid has been described for osteocalcin in bone, for cartilage, intervertebral discs, diverse ocular tissues, brain tissue and for elastin in lung and aorta [60, 63, 78, 79, 81, 84, 86, 91].

A further novel approach, which at present has not been further evaluated, is the estimation of specific deletions of mitochondrial DNA that exhibit an accumulation in soft tissues such as muscle [67].

Historical cases

Although these are "non-forensic" cases, requests concerning historical cases are very frequent in the forensic practice. Indeed some historical cases have a forensic component. For this reason the following remarks should be made:

In well–preserved cases the morphological methods listed in the Tables (methods I–III and V) should be applicable. Although teeth are highly resistant to the rigours of most burial environments, the applicability of histological methods on teeth (III in Table 2A) may be limited because of alterations within the dental microstructure with time [2, 32]. Histological methods are not widely employed in historical cases because they are destructive. If destruction has to be avoided, several non-destructive methods may be applied [48, 50, 51].

The results of biochemical methods based on aspartic acid racemization (IV in Table 2A) have to be interpreted cautiously depending on the time elapsed since death and the postmortem surroundings. In the first few decades after death these biochemical methods are apparently applicable [73]. In cases with postmortem intervals of centuries the pattern of decomposition leads to an apparent "averaging out" of the measured extents of aspartic acid racemization [9, 21]; the biochemical methods are probably only applicable in cases with extreme low temperatures during the postmortem interval [62].

Living individuals

In living individuals the selection of methods has to consider ethical aspects and legal regulations. All methods presented in the Tables as applicable for living individuals (I-IV, Tables 1 and 2 A) require either radiological examinations or dentine sampling by tooth extraction or biopsy [85]. In all cases it is necessary to clarify whether such interventions are acceptable from either an ethical or legal standpoint. Details about legality and ethical justification of methods of age estimation in living individuals with respect to German regulations are given by Ritz and Kaatsch [80].

Final remarks

1. The choice of a method has to consider the specific circumstances of the individual case. In detail, the following questions must be clarified to enable an optimal choice: What accuracy is needed? Which age range is to be expected? Are sex, race and ethnic origin known and to be considered? In cadavers: Which material can be analysed (Elapsed time since death? Environmental factors?)? In living individuals: Which ethical and legal regulations have to be considered?

2. Published data should not be used uncritically for age estimation. Special education and training is required for the application of all effective methods. An adequate calibration by each "user" is to be strongly recommended, in order to avoid systematic errors (e.g. caused by different population characteristics of the reference and target samples) [45, 47].

3. With good reason Houck et al. [33] stated that 'although science often hopes to develop "pure" techniques that can be accurately used by novice and master alike, experience is nonetheless the determining feature of any evaluative process'. Many of the presented methods therefore require specialised and trained laboratories and personnel. This must not be an argument against the selection of a method, if questions with a high legal and social impact for the individual as well as for the community are to be solved. In our era which is characterised by extremely rapid scientific progress resulting in high specialisation of scientists it is acceptable and *lege artis* to consult specialists.

4. Every recommended method is represented by several scientific groups, each of them using their very own methodological protocol and different procedures for evaluation of their method. This leads to severe limitations in comparability, reproducibility and verification. In a time in which quality control has achieved a great importance in all fields of the biomedical sciences it is surprising how few attempts have been made to find common standardisation, calibration and evaluation procedures for methods for age estimation. At the moment, there are no generally accepted guidelines concerning quality assurance in age estimation. The important tool of external quality control is not used at all, although the performance of blind trials would, without any doubt be possible in the field of age estimation. Efforts in these directions are necessary in order to guarantee quality standards and adequate answers to the important legal and social issue of age estimation in forensic medicine.

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