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TITLE PAGE

Title

Quantifying the potential of morphological parameters for human dental identification: Part 3 Selecting the strongest skeletal identifiers in the mandible

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Abstract

The current study aimed to select the best mandibular morphological identifiers.

One hundred eighty-five panoramic radiographs were retrospectively collected, in which four landmarks were located on the mandible: the most superior point of the condyle right/left (CONR/L), of the coronoid right/left (CORR/L), of the mandibular lingula right/left (LINR/L), and the most mesial point of the mental foramen right/left (MMFR/L). Five linear measurements, 6 angles and 10 ratios were measured bilaterally.

Three groups of statistics were considered: (1) mean potential set; (2) inter- observer agreement quantified by intra-class correlation (ICC) and within-subject coefficient of variation (WSCV); (3) Spearman correlation. Parameters were selected for a step-by-step cascade.

In a univariate approach, the following parameters proved to have the best identifying capacity: ratio 3 right (between lines CONR – CORR and LINR – MMFR) with mean potential set 13%, ICC 0.90, WSCV 4.8%; ratio 4 (between lines CONR/L - CORR/L and MMFR - MMFL) with mean potential set 13%, ICC 0.92, WSCV 8.9%; and angle 4 left (between landmarks LINL, MMFL and MMFR) with mean potential set of 18%, ICC 0.91, WSCV 1.2%. The correlation coefficients ranged from 0.01 to 0.33. In a multivariate approach, the identifying capacity improved drastically, with all ratios combined as the strongest identifier (mean potential set 1.29%).

In conclusion, a single ratio or a single angle already narrows down the set of potential matches, but the mean potential set remains relatively large. Combining all ratios drastically increases the certainty of the match.

Keywords

Forensic Odontology · Human identification · Panoramic radiographs · Mandible

Statements and Declarations

The current research was developed after approval of the Ethics Committee of the University Hospitals Leuven, Leuven, Belgium (November 26, 2019). The authors declare that they have

no conflict of interest, and no external funding was received for the execution of this research.
This work was presented at the 73rd Annual Meeting of the American Academy of Forensic Sciences on the 18th February 2021, Anaheim, USA. (Abstract G9).

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MAIN TEXT

Introduction

Human identification is an essential part of forensic science and anthropology. In his chapter "Traits peculiar to the individual", Stewart mentions that anatomical features are valuable in identification due to their high variability and uniqueness [1]. Particularly the bones of the craniofacial skeleton and the teeth show a large variability in size, shape and proportions which can lead to identification [2]. Moreover, they are often among the best preserved parts in human remains, with the mandible persisting in a well-preserved state longer than any other bone [3,4]. This is due to its dense layer of compact bone.

Since the mandible is the only detachable bone of the skull, it might be found separately at a crime scene or in a mass disaster. Additionally, the mandible is the last skull bone to cease development, with different maturation and growth patterns in males and females [5,6]. All these characteristics favour the use of the mandible for identification.

On radiographs, potential morphological identifiers of the mandible include the mental and mandibular foramen, the condyle, the coronoid and the mental symphysis [7,8]. Several authors studied the mental and mandibular foramina, with specific attention for their size [2,7,9,10], location and symmetry [8,11–14]. However, the authors mainly focused on age estimation and sex determination [5,15–23] rather than the identifying capacity of the mandibular morphological traits. Only one study focused on identification [24] and suggested that cone beam computed tomography ((CB)CT) of the mandibular midline canal structures may be useful. Still, their sample consisted of only 10 subjects with a (CB)CT at two different moments in time.

The gold standard of odontological identification relies on comparisons of dental treatment, morphology, and morphometry between ante-mortem (AM) and post-mortem (PM) findings. However, the decrease in dental restorations reduces the occurrence of unique dental identifiers [25]. Moreover, dental radiographs contain more than only dental information, with panoramic radiographs also depicting the entire mandible. Thus, the current study aimed to determine the mandibular morphological traits with the strongest identifying capacity.

Materials and methods

Study population

This project was approved by the KU Leuven Ethics Committee. The owner of a private dental clinic in Brussels, Belgium gave written permission for the data collection. One hundred eighty-five digital panoramic radiographs were retrospectively collected from 94 male and 91 female subjects in the age range between 16 and 66 years old. The panoramic radiographs were digitally captured according to the manufacturer's recommendations for positioning and exposure with VATECH PAX-i3D Smart, and VATECH PAX400 (VATECH Co., Hwaseong, Korea) between 2009 and 2019. Besides the panoramic radiographs, the patients' age and sex were extracted from the files. Finally, all data were anonymized.

The panoramic radiographs met the following inclusion criteria: good image quality, allowing to register anatomical landmarks of interest bilaterally and showing no signs of skeletal pathology.

Image analysis

The panoramic radiographs were imported in image enhancement software (Adobe Photoshop Version 20.0.7, Adobe System Incorporated, San Jose, CA, USA). Four landmarks were located bilaterally on the mandible, namely the most superior point of the condyle right/left (CONR/L), the most superior point of the coronoid right/left (CORR/L), the most superior point of the mandibular lingula right/left (LINR/L) and the most mesial point of the mental foramen right/left (MMFR/L) (**Fig. 1**). For landmark placing, a magnification of 200% and the brush tool (pixel size 6) were used. Contrast, brightness and gamma exposure were adjusted to detect the best landmark position.

The landmarks were used to draw connecting lines and to perform linear and angular measurements, bilaterally (R/L) as follows (**Figs. 1 and 2**, **Table 1**): lines AR/L between CONR/L and CORR/L, lines BR/L between CONR/L and LINR/L, lines CR/L between CORR/L and LINR/L, lines DR/L between LINR/L and MMFR/L and line E between MMFR and MMFL. The angular measurements (A) were: A1 between the lines AR/L and BR/L, A2 between AR/L and CR/L, A3 between BR/L and DR/L, A4 between DR/L and E, A5 between BR/L and CR/L and A6 between CR/L and DR/L.

Vertical and horizontal guide lines were dragged to the centre of the landmarks. The line and ruler tools (set in pixels) were used with snap to-function to draw the connecting lines and to quantify the measurements. Next, ratios (R) of all linear measurements were calculated as follows (**Table 1, Fig. 2**): R1 between lines AR(L) / BR(L), R2 between lines AR(L) / CR(L), R3 between AR(L) / DR(L), R4 between AR(L) / E, R5 between BR(L) / CR(L), R6 between BR(L) / DR(L), R7 between BR(L) / E, R8 between CR(L) / DR(L), R9 between CR(L) / E and R10 between DR(L) / E.

Linear measurements were discarded for analyses, because they are not reproducible between images taken on different times in life (AM versus PM). Even small differences caused by different machines, different settings and different positioning will affect the linear measurements to a greater degree than the proportions and angles. By contrast, angles and ratios can be expected to show a higher degree of reproducibility. The accuracy and reproducibility of measurements is based on the quality of the radiographs [16], their magnification and geometric distortion, as well as on positioning errors [6]. Possible geometric distortions were compensated using dimensional ratios. Moreover, ratios are useful in forensic practice normalising measurements and allowing the comparison between panoramic radiographs from different units without the need of resizing them first.

Forty-one parameters (**Table 1**) were measured (linear measurements, angles and ratios) on both sides of each radiograph by a single examiner. To check for inter-observer reliability, 72 panoramic radiographs (39%) were randomly selected and re-evaluated by two additional observers.

Statistical analysis

Data were collected using Microsoft Excel 2010 and were transferred to SAS software, version 9.4 of the SAS System for Windows. All analyses were based on the first measurements performed by the main observer on the total dataset of 185 subjects, unless otherwise specified.

Note that it is not sufficient to evaluate the number of observed unique values relative to the total number of subjects in order to quantify the uniqueness of a parameter (**Table 2**). Even if all subjects have a unique value, a parameter might be of low use for subject identification if the measurement has a low reliability.

Therefore, the identifying capacity of the parameters was determined and quantified according to the method proposed by Milheiro et al. [26] and Shu et al. [27], using the intra-class correlation coefficient (ICC) and the mean potential set. Additionally, in the current study we considered the within-subject coefficient of variation (WSCV). Note that the WSCV could not be considered in the study by Shu et al. because it is only meaningful if the parameter has a true zero point (e.g. angles). This is not the case for a log ratio, since values can be negative. Thus, the WSCV was not used for ratios. A parameter with a low mean potential set value, high ICC and (if applicable) a low WSCV was evaluated as a strong identifier. This way, a selection of parameters was conducted to establish a cascade of steps to take in the identification process; with each step, the set of possible matches narrows down. When certain parameters proved to be correlated, an alternative was selected. After all, highly correlated parameters would provide similar information, and would very unlikely aid in the identification process.

Figure 3 illustrates how a cascade of steps was established in a univariate approach, considering three groups of statistics: (1) mean “potential set”, which represents the percentage of subjects in the AM reference dataset at least needed to be considered in order to detect the target, i.e. the unknown subject (**Fig. 4**) [26]; (2) inter- observer agreement quantified by ICC and within-subject coefficient of variation (WSCV = the standard error of measurement (SEM) divided by the mean value) [28]; (3) Spearman correlations between parameters.

The univariate cascade provides the user with a practical application of the available parameters, with the benefit of maximally narrowing down the AM dataset. Obviously, narrowing down the AM dataset always implies that the target can be missed. This is reflected by the 95% reproducibility coefficient (RC=2.77 x SEM), which expresses the range of plausible difference between two repeated measurements. In the univariate approach, considering the cases in the AM dataset whose value lies within the range of the target PM case +/- RC as a possible match, would lead to missing the target in 5% of the cases. In the multivariate approach only the values of the mean potential set were used to quantify and rank the identifying capacity of combined parameters.

Results

Univariate approach

Table 3 reports the results of the univariate analysis with mean potential set values ranging between 13% and 30% (**Fig. 5**). Initially, the following best performing parameters were considered for the cascade: R7R or R7L with a mean potential set of 13%, R4R or R4L with a mean potential set of 13%, and A4L with a mean potential set of 18%. Since the mean potential set is a function of the inter-observer reliability, these parameters also demonstrated high inter-observer agreements (**Table 4**): R7R (ICC 0.92, WSCV 14.5%), R7L (ICC 0.91, WSCV 13.9%), R4R (ICC 0.92, WSCV 8.8%), R4L (ICC 0.91, WSCV 8.9%) and A4L (ICC 0.91, WSCV 1.25%). Considering all parameters, the inter-observer ICCs ranged from 0.61 to 0.92.

Next, the correlation coefficients were checked between R7, R4 and A4L to confirm if these parameters would contribute individually to the identification process. The correlation coefficient between R7 and R4 equaled 0.80, indicating they provide largely similar identifying information. Thus, R7 was replaced by R3R with a mean potential set of 13%, ICC 0.90 and WSCV 4.8. The correlation coefficients between the parameters in the new cascade (i.e. R3R, R4 and A4L) ranged from 0.01 to 0.33, indicating they provide complementary rather than overlapping identifying information.

Multivariate approach

Combining parameters significantly improved the identifying capacity, with potential set values ranging from 1.29% to 6.35%. High performing combinations of parameters (**Fig. 6**), that proved to have the best identifying capacity were the following: all ratios combined (20 parameters) with a mean potential set value of 1.29%; all angles combined with all ratios (32 parameters), with a mean potential set value of 1.33% and all angles (12 parameters), with a mean potential set value of 2.60% (**Table 5**).

Discussion

Cascades for practical application

The mandible contains multiple potential morphological identifiers with clear differences in their identifying capacity. Previous reports have highlighted changes occurring in the basal bone throughout life, with increasing age, and changing dental status (due to mastication forces [2,5,19,29]). Those changes are reflected in parameters such as the gonial angle [21]. For this reason, the current study only focused on the condyle, coronoid and the mandibular and mental foramen. Although these mandibular landmarks have proven useful in sex and age estimation studies [8,30], they have not been studied in the context of identification.

In the current study, a selection of parameters was conducted to establish cascades for a univariate approach (high caseload, e.g. mass disaster) as well as a multivariate approach (low caseload, e.g. suspicious death of one individual). Based on our study sample, the following cascade is recommended to maximally reduce the AM dataset in a univariate approach: first determine R3R, followed by R4 bilaterally and then A4L. The parameters can also be used individually, separate from the cascade. In this situation, if one of the landmarks is not present or clearly depicted, the user has the possibility to choose another step not involving the landmark in question. When the lingula of the mandibular foramen is problematic to identify, it is recommended to replace R4 with R7. After all, those parameters are highly correlated, so they provide similar identifying information. Note that although this cascade was optimal in our study sample, the differences in identifying capacity were relatively small among numerous parameters. Thus, in certain samples, other parameters might be equally useful. Still, our proposed cascade is a good way to start the process of identification. Regarding the multivariate approach, it is recommended to calculate all the ratios. Further steps do not seem useful since the combination of all ratios is already expected to render a majorly narrowing down of the possible matches.

Study limitations and future prospects

The current study faced three limitations. Firstly, it is not standard practice to take PM panoramic radiographs, hence, they are less frequently available than PM periapical radiographs and bitewings. Still, PM panoramic radiographs have been proven to be just as useful as ordinary radiographs [31]. However, a PM full body computed tomography (CT) scan is often available, which can be used to reconstruct a panoramic radiograph. Unfortunately, to date, only one study has reported the successful use of reconstructed panoramic radiographs from spiral CT in human identification [32]. It would be useful for future studies to focus on a standardized way to reconstruct panoramic radiographs from CTs. Future research can verify whether our proposed method can be used to find a correct match between AM panoramic radiographs and PM reconstructions or even between AM panoramic radiographs and direct measurements done with callipers on the available skull parts, for example in skeletonized remains, detached mandibles found at the scene, or jaws removed during the identification process.

Still, since panoramic radiography is a widely spread medical imaging technique used for diagnostics and treatment planning in the dental practice, it is frequently part of the AM dental files. It has the advantage of providing information on the entire dentition and the jaw bones [5,23,31,33], and it has been reported to allow for reproducible and accurate linear and angular measurements on the mandible [6]. Furthermore, panoramic radiographs are a useful tool to transfer information in an objective way, overpassing linguistic barriers often encountered in AM files [31].

Secondly, AM panoramic radiographs might date back years before the time of death, and changes may have occurred in that time. Since the shape and position of the mandible changes with age, its appearance on the PM panoramic radiograph might differ significantly from that on the AM radiograph. Still, we specifically selected landmarks that are less prone to age-related changes, for instance avoiding the gonial angle, whose change is very pronounced during the course of life. Moreover, in practice, the examiner of the PM information is not the same as the examiner(s) of the AM information, which might hinder the comparisons between PM and AM measurements. By considering landmarks that are less prone to change, the possible hindering effect on the identifying capacity was minimized in the current study. Furthermore, no edentulous patients were included in the current study, while edentulism is still prevalent, despite the current increased focus on preventive dentistry [34,35]. Periodontitis still affects 20-50% of the world population [36] and it is the most important reason for tooth loss after caries [37]. Moreover, teeth might get lost PM if the patient suffered from periodontitis during the last months of his/her life. Therefore, the cascades proposed in the current study should be validated for identification in edentulous cases.

Thirdly, concerning the low visibility of the coronoid and mandibular lingula, using CBCT imaging might improve the detection of landmarks, leading to more precise measurements. A further improvement, mainly of the reproducibility, might be achieved by machine learning algorithms. After all, once a machine learning approach can detect the landmarks, calculating the ratios and angles goes automatically and the software can be trained to detect the closest matches.

Conclusion

Morphological mandibular traits hold a significant potential as identifiers. Four mandibular landmarks on each side can be used to calculate ratios of measurements and to define angles. In high caseload assignments, a single ratio or a single angle already narrows down the set of potential matches. In a univariate approach, the recommended cascade includes R3R, R4 and A4L. However, a multivariate approach (all ratios) drastically increases the certainty of the match, and is therefore recommended, especially in low caseload assignments.

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Tables

Table 1: Bilateral parameters (linear measurements, angles, ratios) measured on panoramic radiographs (Fig. 2)

Measurement group	Measurement	Description
Linear	AR/L	Measure between CONR/L and CORR/L
	BR/L	Measure between CONR/L and LINR/L
	CR/L	Measure between CORR/L and LINR/L
	DR/L	Measure between LINR/L and MMFR/L
	E	Measure between MMFR and MMFL
Angles	A1	Angle between AR/L and BR/L
	A2	Angle between AR/L and CR/L
	A3	Angle between BR/L and DR/L
	A4	Angle between DR/L and E
	A5	Angle between BR/L and CR/L
	A6	Angle between CR/L and DR/L
Ratios	R1	AR(L) / BR(L)
	R2	AR(L) / CR(L)
	R3	AR(L) / DR(L)
	R4	AR(L) / E
	R5	BR(L) / CR(L)
	R6	BR(L) / DR(L)
	R7	BR(L) / E
	R8	CR(L) / DR(L)
	R9	CR(L) / E
	R10	DR(L) / E

R = right; L= left. CONR/L = the most superior point of the condyle; CORR/L = the most superior point of the coronoid; LINR/L = the most superior point of the mandibular lingula; MMFR/L = the most mesial point of the mental foramen

Table 2: Number of unique values in a total of 502 registrations. Based on the main observer’s measurements

Parameter	Unique values N	Percentage
AR	492	98.01%
BR	495	98.61%
CR	495	98.61%
DR	496	98.80%
A1R	285	56.77%
A2R	294	58.57%
A3R	238	47.41%
A4R	253	50.40%
A5R	332	66.14%
A6R	371	73.90%
E	493	98.21%
AL	489	97.41%
BL	497	99.00%
CL	496	98.80%
DL	493	98.21%
A1L	295	58.76%
A2L	278	55.38%
A3L	238	47.41%
A4L	264	52.59%
A5L	321	64.07%
A6L	368	73.31%
R1R	502	100.00%
R2R	502	100.00%
R3R	502	100.00%
R4R	502	100.00%
R5R	502	100.00%
R6R	502	100.00%
R7R	502	100.00%
R8R	502	100.00%
R9R	502	100.00%
R10R	502	100.00%
R1L	502	100.00%
R2L	502	100.00%
R3L	502	100.00%
R4L	502	100.00%
R5L	502	100.00%
R6L	502	100.00%
R7L	502	100.00%
R8L	502	100.00%
R9L	502	100.00%
R10L	502	100.00%

R = right; L= left.

Table 3: The potential of each parameter for identification (univariate analysis)

	Size of potential set (%)		
Parameter	mean	median	<=1%
A1R	30.40%	25.20%	3.50%
A2R	29.60%	24.50%	3.50%
A3R	25.60%	20.80%	3.80%
A4R	19.30%	15.30%	5.00%
A5R	23.10%	18.60%	4.20%
A6R	19.10%	15.10%	5.10%
A1L	27.40%	22.40%	3.70%
A2L	30.10%	25.00%	3.50%
A3L	27.10%	22.30%	3.60%
A4L	**18.00%**	**14.20%**	**5.30%**
A5L	23.30%	18.70%	4.20%
A6L	26.40%	21.50%	3.80%
R1R (log)	15.60%	13.30%	3.90%
R2R (log)	18.90%	16.20%	3.20%
R3R (log)	**12.90%**	**10.90%**	**4.90%**
R4R (log)	**13.00%**	**10.70%**	**5.20%**
R5R (log)	19.80%	17.30%	3.10%
R6R (log)	18.70%	16.30%	3.20%
R7R (log)	**13.60%**	**11.30%**	**5.00%**
R8R (log)	21.90%	19.30%	2.70%
R9R (log)	18.20%	15.30%	3.40%
R10R (log)	15.70%	13.30%	4.00%
R1L (log)	15.70%	13.40%	3.90%
R2L (log)	17.70%	15.10%	3.60%
R3L (log)	14.20%	12.10%	4.40%
R4L (log)	**13.80%**	**11.50%**	**4.80%**
R5L (log)	18.10%	15.70%	3.40%
R6L (log)	19.50%	17.10%	3.10%
R7L (log)	**13.70%**	**11.40%**	**4.90%**
R8L (log)	21.30%	18.70%	2.80%
R9L (log)	17.20%	14.50%	3.70%
R10L (log)	16.10%	13.60%	3.90%

R = right; L= left. <=1%: percentage of subjects with potential set smaller than 1%. Parameters in bold represent the parameters considered for the univariate cascade.

Table 4: Inter-observer reliability for each measurement and ratio

Parameter	Inter-observer agreement		
	ICC (95%CI)	SEM	WSCV
A1R	0.748 (0.676;0.807)	4.020	7.75%
A2R	0.761 (0.678;0.825)	3.752	4.96%
A3R	0.822 (0.717;0.891)	2.112	1.39%
A4R	0.901 (0.858;0.932)	1.822	1.30%
A5R	0.858 (0.808;0.896)	2.931	5.57%
A6R	0.905 (0.875;0.928)	2.406	2.42%
A1L	0.797 (0.733;0.848)	3.543	6.84%
A2L	0.752 (0.666;0.818)	3.533	4.66%
A3L	0.798 (0.643;0.890)	2.408	1.58%
A4L	**0.915** (0.880;0.940)	**1.737**	**1.25%**
A5L	0.856 (0.801;0.897)	3.061	5.84%
A6L	0.812 (0.760;0.854)	3.433	3.44%
R1R (log)	0.845 (0.786;0.888)	0.051	-
R2R (log)	0.801 (0.741;0.847)	0.085	-
R3R (log)	**0.908** (0.881;0.929)	**0.038**	**-**
R4R (log)	**0.929** (0.899;0.951)	**0.053**	**-**
R5R (log)	0.685 (0.595;0.758)	0.074	-
R6R (log)	0.675 (0.572;0.757)	0.062	-
R7R (log)	**0.921** (0.886;0.945)	**0.057**	**-**
R8R (log)	0.627 (0.522;0.713)	0.093	-
R9R (log)	0.847 (0.783;0.893)	0.094	-
R10R (log)	0.877 (0.837;0.908)	0.064	-
R1L (log)	0.839 (0.775;0.885)	0.051	-
R2L (log)	0.838 (0.785;0.879)	0.079	-
R3L (log)	0.870 (0.831;0.900)	0.041	-
R4L (log)	**0.914** (0.885;0.936)	**0.054**	**-**
R5L (log)	0.750 (0.669;0.813)	0.063	-
R6L (log)	0.614 (0.501;0.706)	0.065	-
R7L (log)	**0.918** (0.881;0.943)	**0.055**	**-**
R8L (log)	0.657 (0.555;0.739)	0.089	-
R9L (log)	0.862 (0.800;0.906)	0.084	-
R10L (log)	0.865 (0.821;0.898)	0.064	-

R=right; L=left. ICC=intraclass correlation. CI=95% confidence interval based on Fishers transformation of the ICC. WSCV=within-subject coefficient of variation. Parameters in bold represent the parameters considered for the univariate cascade. SEM=standard error of measurement

Table 5: The potential of possible combinations of parameters for identification (multivariate analysis)

Combinations of measurements	N	Mean potential set	<=1%
All ratio parameters	**20**	**1.29%**	**80.97%**
Ratio parameters (Left)	10	2.37%	68.30%
Ratio parameters (Right)	10	2.92%	64.67%
All angles	12	2.60%	65.98%
Angles (Left)	6	6.35%	40.78%
Angles (Right)	6	4.73%	47.15%
All ratio parameters (mean values)	10	2.71%	66.23%
All angles and ratios	32	1.33%	81.85%
All angles (mean values)	6	5.26%	47.75%

N = number of parameters used for identification. The mean potential set is the mean expected percentage of subjects in the population (the reference database) being at least as close to the correct subject as the subject itself. The lower the mean potential set, the more useful the variable in identifying the correct subject. <=1%: percentage of subjects for which the potential set is smaller than 1%. Parameters in bold represent the parameters considered for the multivariate cascade. (**Fig. 3**)

<u>Figures' legends</u>

Fig. 1: Skeletal landmarks located on the mandible.

Fig. 2: Linear measurements and angles measured on panoramic radiographs.

Fig. 3: Hypothetical scenario illustrating how the cascade can be put into practice. Note that the numbers of radiographs were chosen arbitrarily, both for the starting point and at the different steps in the cascade. In this hypothetical scenario, a PM case is to be matched to an AM set of 27 panoramic radiographs. In the AM set, a blue frame and a blue arrow mark the correct match. First, the user has to decide whether to follow a univariate or a multivariate approach. This will be determined by the caseload. In the univariate approach, we recommend starting with R3R as the first step in the cascade. Taking this step narrows down the set of possible AM matches. Further narrowing down is done in step 2 by considering R4. Finally, after considering A4L in step 3, five possible AM matches remain. To improve the chances of finding the exact match, further steps could be taken, be it univariate or multivariate. However, there is never a guarantee that the cascade will lead to an exact match. Other identification methods might still be necessary.

In the multivariate approach, we recommend calculating all ratios. Since this step already includes a lot of information, pursuing a further cascade is expected to be of no value for the identification process.

Fig. 4: Graphic illustration of the concept *potential set* based on a single indicator (univariate approach), assuming the indicator has a normal distribution with a mean value equal to 100, and a standard deviation (SD) equal to 10. Note that this SD is the square root of the total variability. The post-mortem value of the parameter equals 90 in this subject. The ante-mortem value equals 85, which is the target of the identification process. Within the ante-mortem database, 24.2% of the subjects have a closer value than the target. This percentage is defined as the *potential set* and is represented by the grey area. (Figure reproduced with permission from Milheiro et al. [26]).

Fig. 5: Density functions (the total area under the curve equals one), illustrating the identifying capacity of one well performing parameter from the univariate cascade (ratio 4 right with a mean potential set of 13%) and one among the worst performing parameters (angle 1 right with a mean potential set of 30%). The area under the curve left of a considered size of the potential set denotes the percentage of subjects for whom the potential set is

smaller than the considered size. Note that the peak of the curve for ratio 4 right is high and relatively close to zero (5.20% of subjects have a potential set ≤ 1%), which indicates a relatively strong identifier. By contrast, the peak for angle 1 right is more flattened, and the curve stretches more to the right (3.50% of subjects have a potential set ≤ 1%).

Fig. 6: Density function (the total area under the curve equals one) illustrating the identifying capacity of two well performing parameters from the multivariate cascade (all ratios with a mean potential set of 1.29% and all angles with a mean potential set of 2.60%). The area under the curve left of a considered size of the potential set denotes the percentage of subjects for whom the potential set is smaller than the considered size. Note that the peaks of both curves are closer to zero than the ones in Fig. 4, with a higher peak for all ratios (80.97% of subjects have a potential set ≤ 1%) than for all angles (65.98% of subjects have a potential set ≤ 1). Both curves indicate strong identifiers.

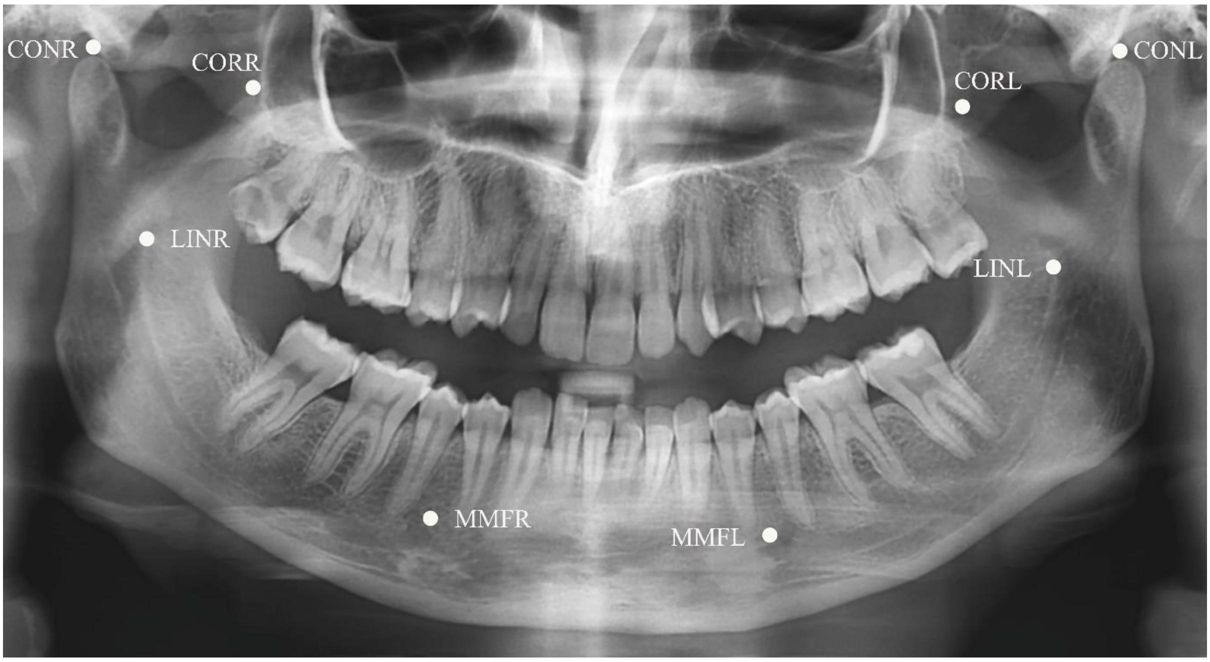

Fig. 1

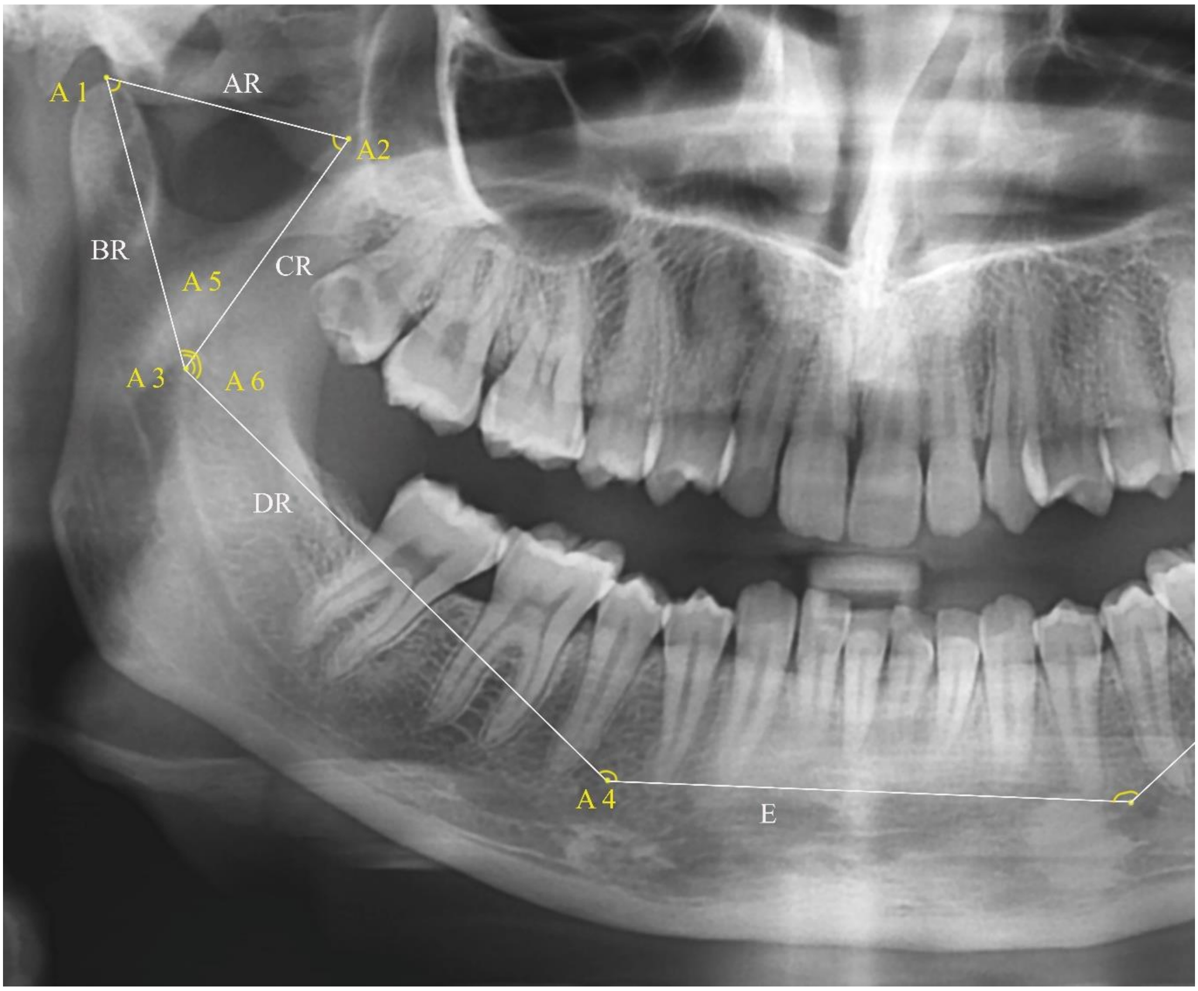

Fig. 2

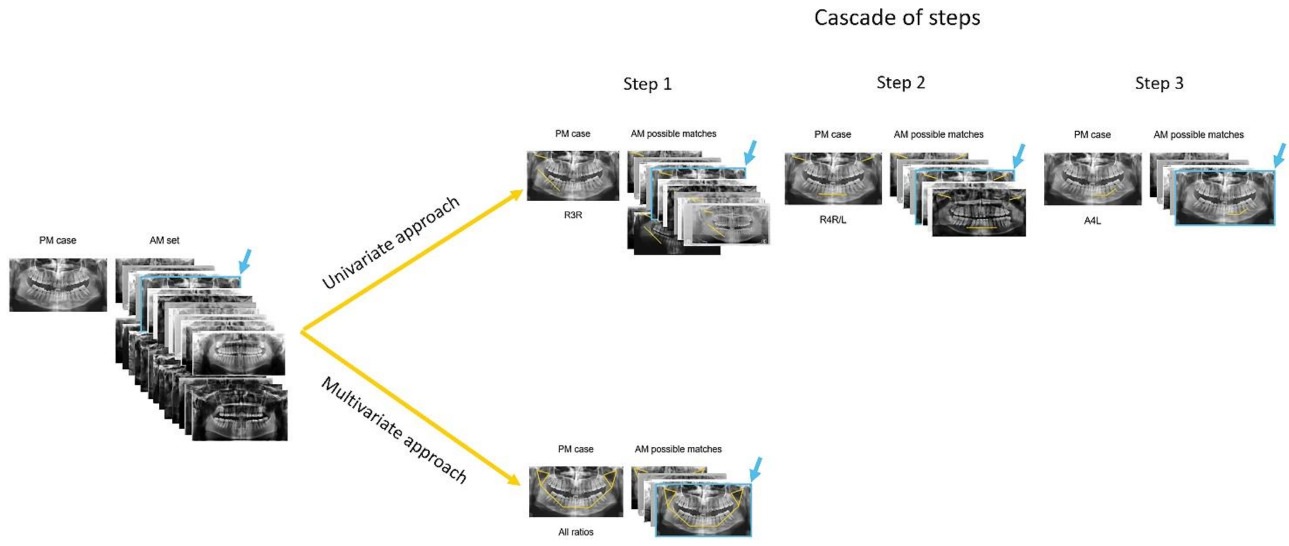
Cascade of steps
Step 1
Step 2
Step 3
PM case
AM set
Univariate approach
Multivariate approach
PM case
AM possible matches
R3R
PM case
AM possible matches
R4R/L
PM case
AM possible matches
A4L
PM case
AM possible matches
All ratios

Fig. 3

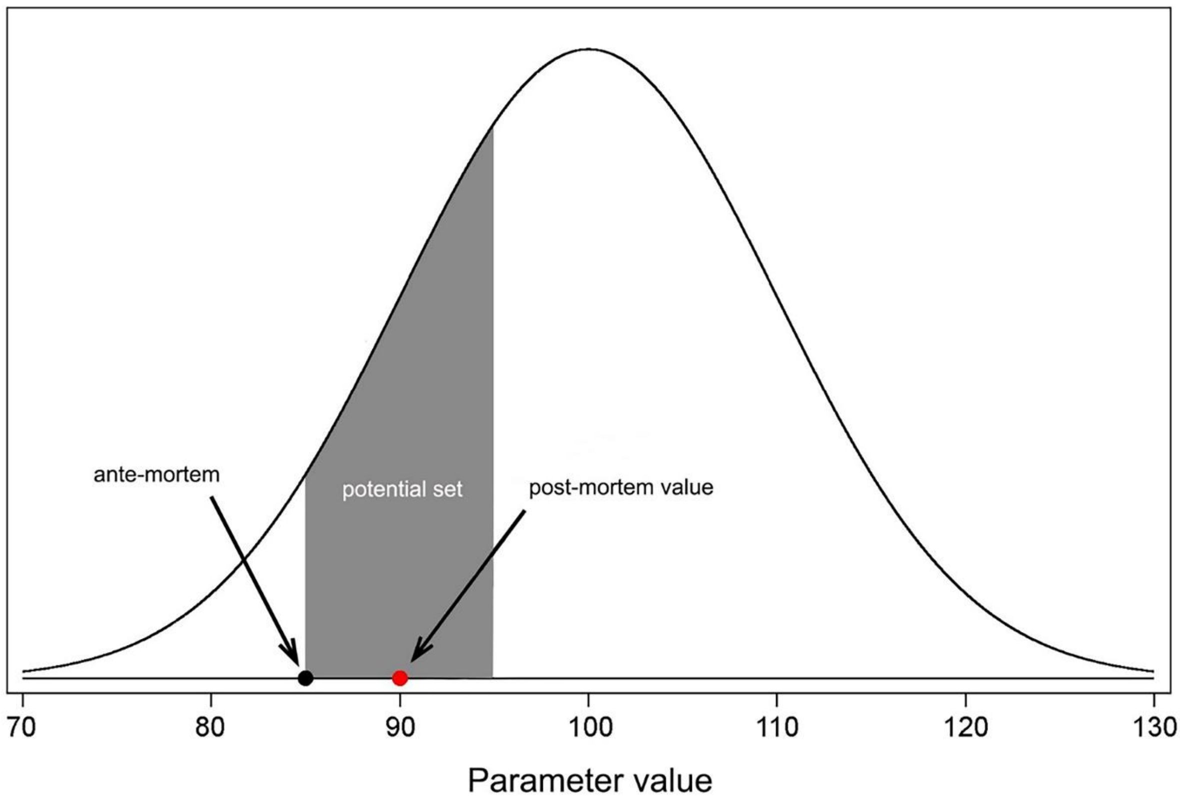
ante-mortem
potential set
post-mortem value
70
80
90
100
110
120
130
Parameter value

Fig. 4

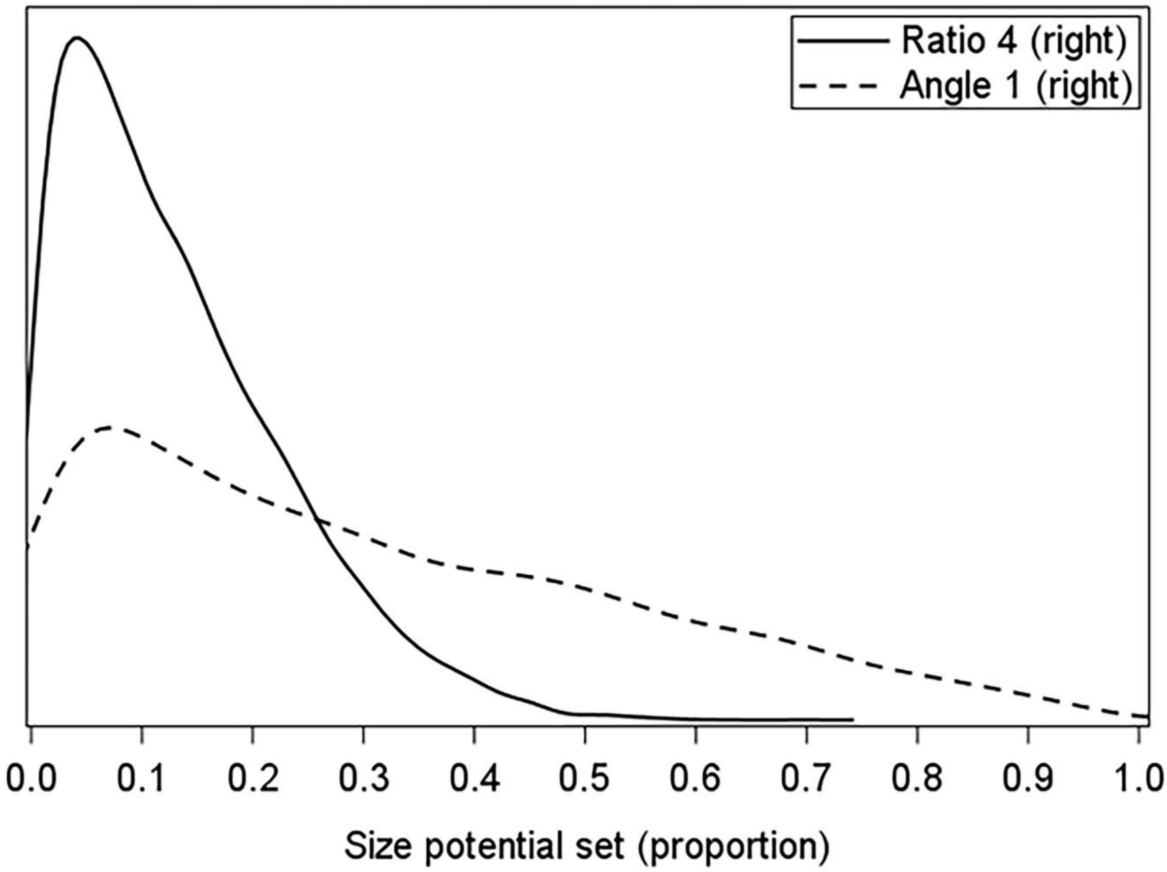
Ratio 4 (right)
Angle 1 (right)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Size potential set (proportion)

Fig. 5

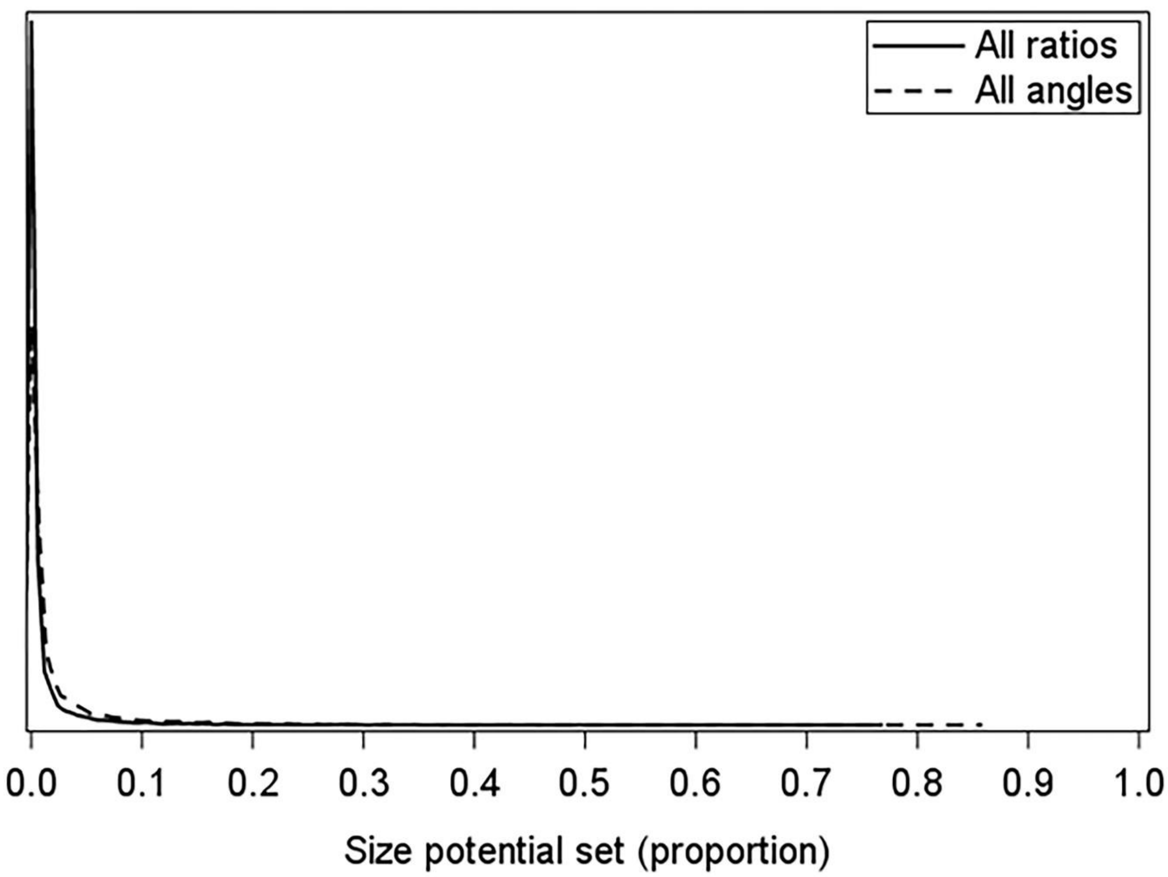
All ratios
All angles
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Size potential set (proportion)

Fig. 6