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QUANTIFYING THE POTENTIAL OF MORPHOLOGICAL PARAMETERS FOR HUMAN DENTAL IDENTIFICATION:

PART 1 PROOF OF CONCEPT

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Quantifying the potential of morphological parameters for human dental identification: Part 1 Proof of concept

Abstract

In forensic identification, lack of eccentric characteristics of intact dentitions hinders correct ante-mortem/post-mortem (AM/PM) matching. It remains unclear which morphological dental parameters hold strong potential as identifiers. This study aimed to establish a method to quantify and rank the identifying potential of one (or a combination of) continuous morphological parameter(s), and to provide a proof of concept.

First, a statistic was defined that quantifies the identifying potential: the mean potential set (MPS). The MPS is derived from inter-observer agreement data and it indicates the percentage of subjects in the AM reference dataset who at least need to be considered to detect the correct PM subject. This was calculated in a univariate and a multivariate setting.

Second, the method was validated on maxillary first molar crowns of 82 3D-digitally scanned cast models. Standardized measurements were registered using 3D modeling software (3-Matic Medical 12.0, Materialise N.V., Leuven, Belgium): tooth depth, angles between cusps, distances between cusps, distances between the cusps and the mesial pit. A random sample of 40 first molars was measured by a second examiner.

Quantifying and ranking the parameters allowed selecting those with the strongest identifying potential. This was found for the tooth depth (1 measurement, MPS=17.1%, ICC=0.879) in the univariate setting, and the angles between cusps (4 measurements, MPS=3.9%) in the multivariate setting. As expected, the multivariate approach held significantly stronger identifying potential, but more measurements were needed (i.e. more time-consuming).

Our method allows quantifying and ranking the potential of dental morphological parameters as identifiers using a clear-cut statistic.

Key words: forensic sciences, forensic odontology, human dental identification, tooth morphology

INTRODUCTION

The human dentition is particular as it comprises a definite arrangement of the teeth, distinct morphological characteristics of each tooth and possible presence of pathology and/or dental treatment. The combined information of these particular features holds a strong identifying potential in case post-mortem (PM) remains of a human body are found.[1, 2] Furthermore, due to their great resistance to peri-mortem and post-mortem events that cause destruction of other body tissues, the teeth are a powerful tool for human identification.

However, classical dental identification methods become increasingly challenging and eventually less powerful, since they are mainly based on comparisons of ante-mortem (AM) and PM dental treatment and pathology registrations. Conversely, the emphasis on prevention and patient education about the etiology of dental caries[3, 4] and periodontal disease[5], combined with improved oral hygiene have resulted in reduced treatment needs and increased numbers of intact, healthy teeth.[6, 7] Therefore, comparing tooth morphology has become an important tool for human identification.[8] Dental morphology can be compared using clinical observation of tooth specific features, such as the position of a cusp in relation to another, or measurements of a tooth surface. This can be useful in an AM or PM context. Metric comparisons can be made with a caliper or computer-aided using digital images. Geometric shape analysis by superimposition of digital images of teeth or tooth parts may also contribute to identification based on morphological features[9, 10], using two and/or three-dimensional medical registrations.[10, 11] Still, numerous morphological parameters can be considered, and it remains unclear which ones hold a strong potential as identifiers, i.e. which ones are most unique.

In the forensic literature, attempts have been reported to determine *uniqueness* of the human dentition or parts of it. Morphological patterns of the anterior teeth have been analyzed in the context of human bite mark examinations.[12–14] Yet, uniqueness of the human dentition lacks sustainable proof.[9] Also in the fields of fingerprint or handwriting analysis, ideals of unique features have been sought. Although it would hypothetically be of value for the forensic practice, the belief of unique features to each individual is rather naive. In mathematics and logic, the term "uniqueness" refers to the property of being the one and only object satisfying a certain condition, i.e. “no two objects are ever the same”. In fact, one may question this proposition, as studies are mandatorily done in a closed set of individuals and as such cannot represent the global population, even when advanced statistics are applied. Furthermore, the idea of the need to establish uniqueness to achieve identification is somewhat obsolete. This holds especially true in a legal context: it is less important to rely on a “unique” feature of the individual´s dentition than to systematically prove the veracity of one´s actions within the present evidence. Thus, although thoroughly intended, the uniqueness of the human dentition has not yet been proven. In the lack of established uniqueness, the reliability of forensic evidence analysis is of utmost importance.[15, 16]

Nevertheless, in specific situations, especially in a closed scenario where the individuals are known and great amounts of information is present, identification may be possible based on individual characteristics. Evaluation of the morphology of the crowns of posterior teeth by means of metric measurements and non-metric shape analysis by superimposition of AM/PM images (i.e. photographs of an AM cast model and PM photographs of the cast model obtained from the remains) has been reported as useful in the identification of a victim of a car accident.[17] Photographs and radiographs are commonly taken in a clinical dental context to define a treatment plan or as auxiliary diagnostic tools. They register clinically detectable dental identifiers which were validated for human identification purposes, with morphological identifiers being the most unique, compared to treatment-based identifiers.[10]

The current study aims to establish a method to quantify and rank the identifying potential of one (or a combination of) continuous morphological parameters, and to provide a proof of concept for this method using a sample of 3D first molar scans.

MATERIALS AND METHODS

Quantifying the potential for identification

Mean potential set (MPS)

Fig. 1 provides a summary overview of the method we propose in the current study.

To quantify the potential of a dental parameter for subject identification, it is not sufficient to evaluate the number of observed *unique* values relative to the total number of subjects. After all, even if each subject has a unique value, a parameter might be of limited use for subject identification if it has a low inter-observer agreement. In practice, the parameter will be compared between a PM unknown subject and the AM reference database. Typically, the examiner of the PM information is not the same as the examiner(s) of the AM information. Therefore, we used the inter-observer agreement to quantify the potential of a parameter for subject identification. More specifically, we studied the between-subject variability and within-subject variability. Intuitively, the lower the within-subject variability σ_W^2 (due to different examiners) relative to the between-subject variability σ_B^2, the higher is the inter-observer reliability and the more useful the measurement for identification. The intra-class correlation coefficient (ICC), being the ratio of σ_B^2 and the total variability ($\sigma_B^2 + \sigma_W^2$) can therefore be used in a univariate setting to compare different parameters regarding their potential for subject identification.

However, instead of solely focusing on the ICC we have introduced another quantification also based on both sources of variability: the *potential set* (Fig. 2). A mean potential set (MPS) of candidate matches was established, referring to the expected number of possible matches that at least needed to be considered for the correct subject not to be excluded. In fact, the MPS refers to the expected percentage of subjects in a population (e.g. an AM database) being as likely to match (or more likely) as the true subject. The percentages of subjects in the subset for whom the potential set was smaller than 20%, 10%, 5% and 1% of the complete sample were also calculated. The reason to use the potential set was twofold. First, the potential set has a more relevant interpretation in the current setting, compared to the ICC. Second and more important, the potential set allowed extrapolating the established method to the multivariate setting, i.e. the quantification of the identifying potential of a combination of parameters. The intuitive interpretation of the potential set is "the proportion of subjects in the AM reference dataset who at least need to be considered in order to detect the target subject, i.e. the unknown subject in the AM reference dataset who corresponds with the examined PM subject".

Hence, the lower the MPS of a parameter or a set of parameters, the higher the identifying potential.

Univariate setting

To calculate the potential set in the univariate setting, we proceeded as follows for each parameter:

- We simulated 10000 values (i=1,…,10000) from a normal distribution with variance σ_B^2. These were values which were not observed (*latent* values) and served only as a starting point to generate the AM and the PM values, respectively.
- For each of these latent values, we simulated two realizations (the AM and the PM values), adding for both a normal variate from a distribution with variance σ_W^2. These realizations were referred to as y_{AMi} and y_{PMi} (forming a pair of measurement referring to the same subject). These values from all subjects constitute the AM set and the PM set, respectively.

- For a value y_{PMi} we calculated the proportion of values in the AM set which were closer to y_{PMi} than the value y_{AMi}. This proportion was referred to as the *potential set* and can be calculated analytically or estimated using all simulated y_{AMi} values.
- We did this for each of the 10000 y_{PMi} values.
- This method allowed to calculate the *mean potential set* (over the 10000 subjects) as well as the percentage of subjects with a potential set smaller than a certain cut-off.

Multivariate setting

For the multivariate setting (i.e. the combination of parameters for subject identification) we followed the same approach. In the multivariate setting, the between- and within-subject variability refer to covariance matrices Σ_B^2 and Σ_W^2. These matrices were obtained by fitting a multivariate mixed model on the data from all observers, using a random intercept for each parameter. These random intercepts were allowed to be correlated (Σ_B^2 is the covariance matrix of these random intercepts) as were the error components (Σ_W^2 is the covariance matrix of these error components). Given the number of parameters, it was not feasible to fit this model directly. Instead, a pairwise approach was used.[18]

Corresponding with the univariate approach, 10000 values were drawn (albeit now for each combination of parameters instead of for each parameter separately), followed by the creation of the realizations y_{PMi} and y_{AMi}. These realizations were now multivariate instead of univariate. To quantify the distance between these two multivariate measurements, the Mahalanobis distance was used.[19]

Analyses were performed using SAS software, version 9.4 of the SAS System for Windows.

Test sample

To provide a proof of concept of the established method, dental morphological parameters which were expected not to differ much between subjects were selected, since they are the least likely to lead up to a positive identification. Therefore parameters measured in upper first molar crowns were chosen.

A sample of 82 dental cast models, three-dimensional (3D) digitally scanned, were retrospectively selected from dental record files at the University Hospital UZ Leuven. The images were saved as stereolithography (STL) file format. Upper 3D scanned dental cast models were selected with right and left intact and fully erupted first molars, from Belgian female and male subjects ranging in age between 7 and 12 years of age. This age range further reduced the variability in upper first molar morphology, because the effect of tooth wear was negligible. 3D scanned dental cast models with incomplete registration of the first molars, first molars with caries, restorations, marked wear of the cusps or orthodontic brackets were excluded.

The scanned dental cast models were imported into 3-Matic Medical 12.0 software (Materialise N.V., Leuven, Belgium). The first molars were segmented from each scanned dental cast model and the anatomic crowns isolated for standardized dimension registrations. On all right and left maxillary first molars, five landmarks were indicated, which rendered 15 measurements. A detailed description of the measurements is provided in Fig. 3. The 15 measurements were classified into four groups: tooth depth (1 measurement, in mm), distances between the cusps (6 measurements, in mm), distances between the cusps and the mesial pit (4 measurements, in mm), and angles between cusps (4 measurements, in degrees). In the analyses, the identifying potential was studied for each dental parameter separately, as well as for groups of parameters

The central pit has been used by other authors as a landmark for various cusp dimensions, since it is a characteristic of upper molars that is easily allocated.[11] In the current study, the mesial pit was considered as the deepest point of the tooth and it was used as a landmark to establish different measurements. The uniform allocation of the landmarks was facilitated by visualizing the model in transparency with allowing rotating and translating the model in the software. In fact, due to the advanced features of the software, the recognition of the deepest point of the tooth by the two examiners was relatively easy. Furthermore, all measurements were registered three-dimensionally by the software; the landmarks were in different planes according to the allocation on the model. This allowed for a semi-automated measurement calculation, improving the reproducibility.

All measurements were registered by a first examiner. After a month, a subset of 20 scanned dental cast models (40 teeth) was randomly selected and re-analyzed by the first and a second examiner.

In the main analysis, no distinction was made between information from left and right teeth. In an additional analysis, this distinction was made, yielding 30 measurements per subject for identification. Note however that results considering left and right as separate parameters were based on inter-observer data based on only 20 cases, as opposed to the 40 cases used for evaluation of the inter-observer reliability in the main analysis. Hence, these results were less stable.

Fig. 4 shows the application of the suggested method to the dental parameters we selected in our test sample.

Results

Univariate setting

Based on a single measurement, the MPS ranged between 17.1 and 32.2%. The strongest identifier was tooth depth, as it presented the lowest mean potential set (17.1%) and a high ICC (0.879). This was followed by the distance between the distal cusps (MPS=19.9%; ICC=0.855) and the distance between the mesial pit and the disto-palatinal cusp (MPS=20.9%; ICC=0.840).

Multivariate setting

Based on a combination of measurements, the MPS ranged between 2.6 and 24.1%. The strongest identifier was the distance between the mesial pit and the cusps, combined with the angles between the cusps, presenting the lowest mean potential set (2.6%), but at a cost of an increased number of measurements (8). Combining the information of the right and left molar only increased the identifying potential of measurements between the mesial pit and the cusps (MPS=5.0% for the 8 measurements versus MPS=7.8% for the 4 measurements) (Table 2).

Discussion

Situating the method in literature

The rationale behind the development of the current method was the lack of clear guidelines on which morphological dental parameters, and in particular combinations of parameters, may have the strongest potential as identifiers. As a result, the choice of one or more parameters is dependent on the case at hand, based on the available AM and PM data, and is subjective to the examiner's expertise and qualification.[21] This is mainly due to the abundant possible dental parameters that could be used as identifiers, and the lack of studies that quantify the identifying capacity of those parameters. A series of case reports can be found in literature, where different parameters were used to achieve victim identification. These are, however, case-specific, depending on which information is available, and the analysis can be made through radiographs, photographs or clinical observation of morphologic features.[10, 17, 22–25]

To our knowledge, no standardized approach has been attempted. In one study, the pattern of the central fissures showed important variation in digital imaging and was proposed as an important parameter for subject identification.[26] Another study from our research group aimed to quantify clinically detectable dental identifiers using mean potential sets [10], but different to the current method, inter-observer agreement was not taken into account and discrete variables (e.g. the presence or absence of a certain feature) were analyzed.

Using continuous parameters implicates that theoretically, a unique parameter value can be observed for every subject. In fact, the observed number of subjects with a unique value depends on the number of decimals used in the chosen measurement system. The current study results were based on digital length and angle measurements with two decimals, expressed in millimeters and degrees respectively. This approach potentially increases the uniqueness of the parameters, compared to (combinations of) features being present or not.

Still, commonly used computer assisted dental identification tools are not based on continuous variables. Instead, ranking is based on an algorithm using dental coding for tooth conditions and treatment. The detail of the coding system and the precision of the algorithm will determine the performance of the program.[27, 28] Furthermore, provided that each system is thoroughly tested, meeting the scientific criteria for reproducibility and subject to peer review, these software tools can reliably give the forensic team an indication of which data collection and comparison protocols to use.[27, 29] A first tool is WinID[30] that combines dental and anthropometric characteristics to rank possible AM/PM matches, sorting for the requested identifiers and considering changes in time. WinID is reportedly reliable for initial sorting of records or identification cases with relatively small amounts of data and especially in the presence of dental treatment.[27, 28] However, when the case load is high and large amounts of records are to be analyzed, the performance of this system is hindered, especially when no AM pathology was registered[31] or significant body fragments are present.[27, 31] A second tool is OdontoSearch[32], which does not compare AM and PM dental records, but assesses the frequency of a certain dental (treatment) pattern in the general population. Therefore, it provides the user with an empirical probability that can be quantified for use in a report or in a court of law. These tools are rather descriptive in contrast with the analytical statistical approach of the current method by which a series of pre-determined parameters is quantified and ranked according to their identifying potential.

Practical application

In forensic practice, the parameters used for identification are determined by the available PM material. We proposed a method to determine which of the available morphological dental parameters has the highest potential for identification. To prove the method's robustness, we applied it in a test sample, focusing on morphological parameters that usually only differ slightly between individuals. In particular we used continuous morphological parameters of the first upper molars, measured on dental cast models that were 3D digitally scanned. Thus, an upper first molar crown was considered as available PM material in this theoretical setting.

In this scenario, a digital dental cast model should be available from all individuals in the AM set and should be obtained from the PM remains. This may be either by scanning existing AM dental cast models, obtained by conventional impression techniques or using AM taken intraoral scans. The PM intraoral scan can easily be obtained using an intraoral scan, as current devices are relatively small, portable, easy to use and provide a fast image acquisition.

A standardized registration of parameters is essential to keep the inter-observer agreement as high as possible. Numerous measurements can be taken in the human dentition, but to be useful as identifiers, they need to be defined unambiguously. In an initial phase of this study an effort was made to take numerous measurements that could contribute to characterize the tooth. Many were excluded due to the great discrepancy of inter-observer agreement.

To determine the potential of a parameter for identification, the mean potential set (MPS) was proposed. This statistic served three purposes: (1) it reflected how "easy" it will be to find the correct subject in a practical context, (2) it allowed quantifying and ranking the potential of different parameters for identification, and (3) it allowed quantifying and ranking the potential of combined parameters for identification. The lower the MPS of a parameter or a set of parameters, the stronger the identifying potential.

In identification assignments, the balance must be kept between gathering as much information as possible, and providing results as soon as possible. Therefore, the current method will help selecting the most suitable parameters for human dental identification. After all, quantifying and ranking the potential of studied parameters for identification allows establishing a workflow of steps that the forensic odontologist can take in actual casework. The workflow will differ in high versus low caseload assignments, with the former requiring a highly efficient (univariate) approach, whereas the latter might require a more elaborate (multivariate) approach. Logically, when considering the usefulness of the measurements in forensic identification practice, not only their identifying potential is relevant. The work and time necessary to obtain the measurements also has to be considered and both weighted in relation to each other. Obviously, the easiest parameter to obtain, with the least number of measurements, will be the most useful for subject identification. Thus, when multivariate approaches have similar MPS, the most useful measurement combination will be the one with the least parameters to consider. Take for example all 30 parameters combined in the right and left upper first molars. Although the MPS of that combination is one of the best (3.4%), the fact that all 30 parameters need to be measured makes it complex and time consuming, and thus impractical. A more useful choice is to measure the four angles between cusps, with a similar MPS of 3.9%. On the same line of reasoning, when univariate measurements have similar MPS, the most useful will be the one which can be obtained the easiest. Tooth depth was found to be the strongest identifier (MPS=17.1%, ICC=0.879). However, to measure tooth depth, all cusp point-landmarks and the point corresponding to the mesial pit had to be placed. As such, tooth depth may not be the most useful measurement but the distance between the distal cusps (MPS=19.9%), as it involves the placement of only two cusp point-landmarks.

Furthermore, over time, changes occur which are important to consider, such as changes in the position of the cusp landmark as a result of abrasive and/or erosive tooth wear, caries or enamel/dentine loss. Consequently, the landmarks will differ in position and related parameter measurements will vary, increasing the mean potential set values. The closer the AM information was obtained to the time of death, the less changes will have occurred, increasing the chances for a positive match.

Study limitations and future prospects

In practice, the potential set is expected to be larger than the values obtained in the current study, since our inter-observer agreement was based on measurements on the same image. By contrast, in practice, the AM and PM registrations are performed at different moments by different observers based on different images. Unfortunately, the variability due to differences in time of image acquisition, image quality, and center-specific measuring techniques were not taken into account in the current study.

Two further limitations can be pointed out. First, it is unlikely that the upper first molars would be the only available evidence. Still, they were suitable to study the proof of concept of our proposed method, and future studies will have to clarify more practical approaches to bring the established method into practice. Second, our current method can only handle continuous data. Nonetheless, expansion of our method to include nominal and/or categorical data could be the subject to future research.

CONCLUSION

Our method allows quantifying the potential of dental morphological parameters as identifiers, and summarizing that potential in one clear-cut statistic, the mean potential set. Consequently, the method allows ranking parameters according to their identifying potential, which can be translated into practice by selecting the most suitable parameters for human identification. The proof of concept was demonstrated, and further studies should clarify which dental morphological parameters hold the strongest potential for human identification.

REFERENCES

1. Madi HA, Swaid S, Al-Amad S (2013) Assessment of the uniqueness of human dentition. J Forensic Odontostomatol 31:30–39
2. Pereira CP, Santos JC (2013) How to do identify single cases according to the quality assurance from IOFOS. the positive identification of an unidentified body by dental parameters: A case of homicide. J Forensic Leg Med 20:169–173. https://doi.org/10.1016/j.jflm.2012.06.004
3. Fejerskov O, Kidd E, Nivad B (2003) Dental Caries: the disease and its clinical management, 2nd ed.
4. Fejerskov O (2004) Changing paradigms in concepts on dental caries: Consequences for oral health care. Caries Res 38:182–191. https://doi.org/10.1159/000077753
5. Tatakis DN, Kumar PS (2005) Etiology and Pathogenesis of Periodontal Diseases. Dent Clin North Am 49:491–516. https://doi.org/10.1016/j.cden.2005.03.001
6. Organization WH World Oral Health Report 2003. Published 2003. Accessed 15 February, 2018
7. (2017) The Global Burden of Disease Study 2016. Disease and Injury Incidence and Prevalence Collaborators. Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990-2016: a systema. Lancet 390:1211–1259
8. Pretty IA, Sweet D (2001) A look at forensic dentistry - Part 1: The role of teeth in the determination of human identity. Br Dent J 190:359–366. https://doi.org/10.1016/j.synthmet.2012.11.026
9. Franco A, Willems G, Souza PHC, et al (2015) The uniqueness of the human dentition as forensic evidence: a systematic review on the technological methodology. Int. J. Legal Med.
10. Angelakopoulos N, Franco A, Willems G, et al (2017) Clinically Detectable Dental Identifiers Observed in Intra-oral Photographs and Extra-oral Radiographs, Validated for Human Identification Purposes. J Forensic Sci 62:900–906. https://doi.org/10.1111/1556-4029.13310
11. Macaluso Jr. P (2010) Sex discrimination potential of permanent maxillary molar cusp diameters. J Forensic Odontostomatol 28:22–31
12. Sweet D, Pretty IA (2001) A look at forensic dentistry - Part 2: Teeth as weapons of violence-

identification of bitemark perpetrators. Br Dent J 190:415–418. https://doi.org/10.1038/sj.bdj.4800990

13. Franco A, Willems G, Souza PHC, et al (2017) Three-dimensional analysis of the uniqueness of the anterior dentition in orthodontically treated patients and twins. Forensic Sci Int 273:80–87. https://doi.org/10.1016/j.forsciint.2017.02.010

14. Kieser JA, Bernal V, Neil Waddell J, Raju S (2007) The uniqueness of the human anterior dentition: A geometric morphometric analysis. J Forensic Sci. https://doi.org/10.1111/j.1556-4029.2007.00403.x

15. Saks MJ, Koehler JJ (2008) The individualization fallacy in forensic science evidence. Vanderbilt Law Rev 61:199–219

16. Page M, Taylor J, Blenkin M (2011) Uniqueness in the forensic identification sciences—Fact or fiction? Forensic Sci Int 206:12–18

17. Johansen RJ, Michael Bowers C (2013) Positive dental identification using tooth anatomy and digital superimposition. J Forensic Sci 58:534–536. https://doi.org/10.1111/1556-4029.12040

18. Fieuws S, Verbeke G (2006) Pairwise Fitting of Mixed Models for the Joint Modelling of Multivariate Longitudinal Profiles. Biometrics 62:424–431

19. Mahalanobis PC (1963) On the generalised distance in statistics. Proc Natl Inst Sci India 2:49–55

20. Eliasziw M, Young SL, Woodbury MG, Fryday-Field K (1994) Statistical Methodology for the Concurrent Assessment of Interrater and Intrarater Reliability: Using Goniometric Measurements as an Example. Phys Ther 74:777–789

21. Balla SB, Forgie A (2017) Identification by comparison of caries free bitewing radiographs : Impact of observer qualifications and their clinical experience. Forensic Sci Criminol 2:1–5. https://doi.org/10.15761/FSC.1000108

22. da Silva RF, Pereira SD, Prado FB, et al (2008) Forensic odontology identification using smile photograph analysis - Case reports. J Forensic Odontostomatol 26:12–17

23. Silva RF, Botelho TL, Prado FB, et al (2011) Human identification based on cranial computed tomography scan - A case report. Dentomaxillofacial Radiol 40:257–261. https://doi.org/10.1259/dmfr/96080236

24. Forrest AS, Wu HYH (2010) Endodontic imaging as an aid to forensic personal identification. Aust Endod J 36:87–94. https://doi.org/10.1111/j.1747-4477.2010.00242.x

25. Almeida SM de, Delwing F, Azevedo JAP de, et al (2015) Effectiveness of dental records in human identification. RGO - Rev Gaúcha Odontol 63:502–506. https://doi.org/10.1590/1981-863720150003000213017

26. Roy J, Rohith M, Nilendu D, Johnson A (2019) Qualitative assessment of the dental groove pattern and its uniqueness for forensic identification. J Forensic Dent Sci 11:42–47

27. Adams BJ, Aschheim KW (2016) Computerized Dental Comparison: A Critical Review of Dental Coding

and Ranking Algorithms Used in Victim Identification. J Forensic Sci 61:76–86. https://doi.org/10.1111/1556-4029.12909

28. Al-Amad SH, Clement JG, McCullough MJ, et al (2007) Evaluation of two dental identification computer systems: DAVID and WinID3. J Forensic Odontostomatol 25:23–29

29. Lynch J, Stephan C (2018) Computational Tools in Forensic Anthropology: The Value of Open-Source Licensing as a Standard. Forensic Anthropol 1:228–243. https://doi.org/10.5744/fa.2018.0025

30. Win ID. In: https://abfo.org/winid

31. Lewis C, Leventhal L (2004) Dental identification software programs compared on disaster size and direction of search. J Forensic Identif 54:572–592

32. Odonto Search. In: http://www.odontosearch.com

Table 1: Identifying potential of the different parameters in the univariate setting, and inter-observer agreement. The considered parameters were: distances between cusps (D), distances between the mesial pit and the cusps (d), and angles between cusps (a). The parameters are ranked according to the mean potential set.

Measurement	Inter-observer agreement	MPS (%)	Size of the potential set# (%)			
			≤1%	≤5%	≤10%	≤20%
Tooth depth	0.879	17.1	3.9	19.0	36.8	64.7
D2: distal	0.855	19.9	3.3	16.6	32.4	57.8
d4: mp-DP	0.840	20.9	3.2	15.8	30.9	55.6
d3: mp-DB	0.834	21.9	3.2	15.4	30.0	53.8
a3: DB-DP	0.864	22.7	4.3	18.0	31.6	53.8
d1: mp-MB	0.767	23.4	2.7	13.3	26.5	50.1
D5: MP-DP	0.795	23.8	2.8	13.8	26.9	49.7
D6: MB-DB	0.770	23.8	2.6	13.3	26.2	49.3
a2: MB-DB	0.848	24.0	4.1	17.2	30.3	51.4
d2: mp-MP	0.777	24.0	2.6	13.4	26.3	49.2
D4: MP-DB	0.787	25.2	2.9	13.6	26.2	47.6
a1: MP-MB	0.805	27.0	3.8	15.5	27.4	46.5
D1: mesial	0.598	29.8	2.0	10.1	19.7	39.1
a4: DP-MP	0.757	29.9	3.5	14.0	24.9	42.7
D3: MB-DP	0.524	32.2	1.8	9.2	17.9	35.7

Legend: Mesio-buccal (MB); mesio-palatinal (MP); disto-buccal (DB); disto-palatinal (DP). mp: mesial pit.

ICC: Intra-class Correlation Coefficient. MPS: Mean Potential Set. #Proportion of subjects for which the potential set is smaller than or equal to the considered size.

Note: The measurements are ordered in decreasing potential for identification, expressed by MPS values. The most powerful measurement was the *tooth depth* (ranked no.1), followed by the *distance between distal cusps* (D2) no.2, and the *distance between the mesial pit and the disto-palatinal cusp* (d4), no.3. The least identifying measurement was the diagonal measurement D3 (*distance between the mesio-buccal and disto-palatinal cusps*), ranked no.15.

Table 2: Identifying potential of the different parameters in the multivariate setting. The parameters are ranked according to the mean potential set.

Measurement combinations	**Nº of parameters**	**MPS (%)**	**Size of the potential set[#] (%)**			
			≤1%	**≤5%**	**≤10%**	**≤20%**
Mesial pit-cusp + angles	8	2.6	64.2	86.6	93.3	97.6
All 30 parameters*****	30	3.4	52.8	80.1	90.2	96.8
Angles between cusps	4	3.9	42.3	76.9	89.2	96.6
Angles between cusps*	8	4.7	55.5	78.4	87.0	93.5
Angles between cusps + depth	5	4.5	45.0	76.1	86.8	95.0
Mesial pit-cusps *****	8	5.0	49.9	75.6	85.7	93.1
Distance between cusps + angles between cusps	10	5.4	51.9	75.8	85.0	92.1
Distance between cusps + mesial pit-cusps	10	5.7	49.8	74.6	83.9	91.6
Mesial pit-cusps + depth	5	6.9	33.7	64.5	78.6	90.0
All parameters except depth	14	7.5	43.8	68.2	78.6	88.2
Mesial pit-cusps	4	7.8	26.2	58.9	75.1	88.8
Distance between cusps + depth	7	7.9	39.3	66.3	77.5	87.7
All 15 parameters	15	8.1	42.0	66.1	77.3	87.0
Distance between cusps	6	10.1	31.4	58.9	71.4	87.0
Distance between cusps*****	12	24.1	23.5	39.0	48.0	59.1

Legend: *****Left and right as separate parameters. [#]Proportion of subjects for which the potential set is smaller than or equal to the considered size.

Note: The measurements are ordered in decreasing potential for identification. The strongest measurement combination was the *mesial pit-cusp + angles*, ranked no.1. The weakest measurement combination was the *distance between cusps*, when both right and left upper molars were considered, ranked no.15.

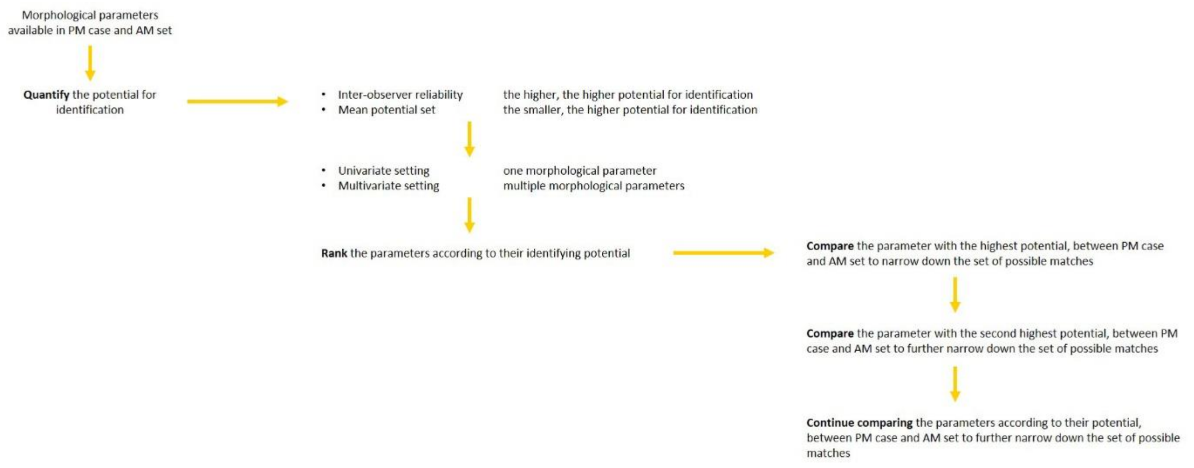

Fig. 1 Schematic representation of the suggested method in casework for forensic identification. The selection of morphologic parameters is specific for each case in hands. Any available morphological structure with measureable features (continuous variables; e.g. distances, angles) may be included (for example skeletal parameters). Note that the morphological parameters are continuous variables (e.g. distances, angles).

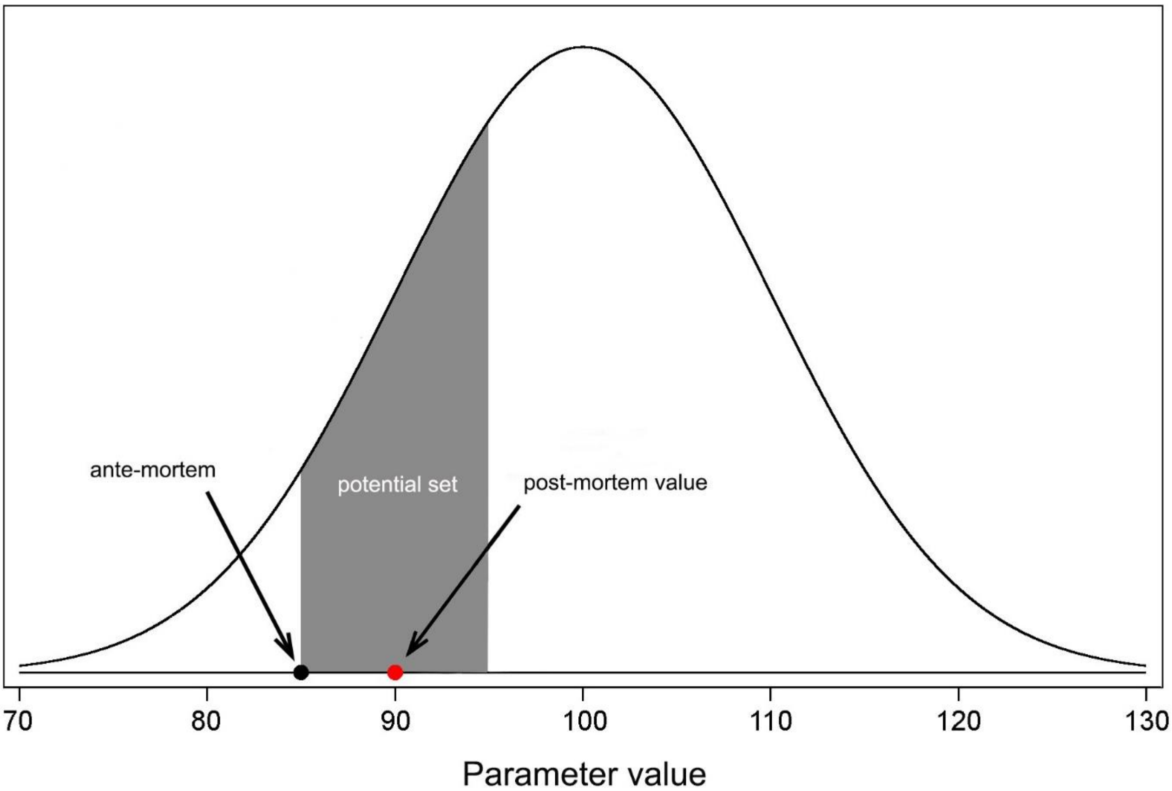

Fig. 2 Graphic illustration of the concept *potential set* based on a single parameter (univariate setting), assuming the parameter has a normal distribution with a mean value equal to 100, and a standard deviation (SD) equal to 10. Note that this SD is the square root of the total variability ($\sigma_B^2 + \sigma_W^2$). 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.

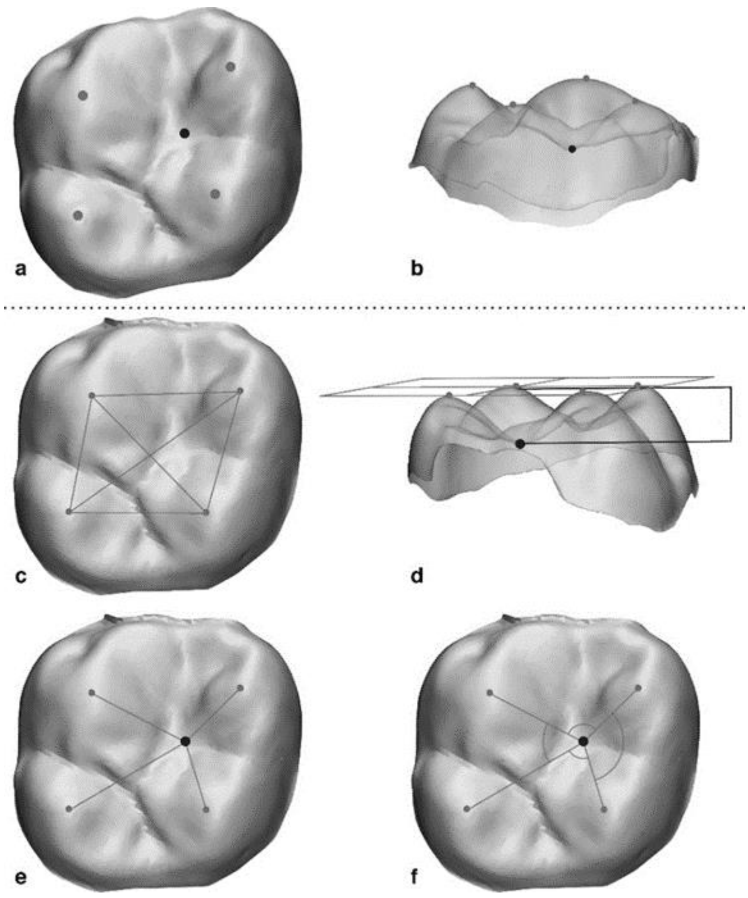

Fig. 3 Landmark placement and measurements obtained from the isolated anatomic crown of tooth 26, using 3-Matic Medical 12.0, (Materialise N.V., Leuven, Belgium).

Upper panels: Landmarks were manually placed after evaluating the model from various points of view with rotation, translation and variations in transparency of the model. a. Cusp point-landmark, occlusal view: the highest point of each cusp (n=4) (gray dots). Mesio-buccal (MB), mesio-palatinal (MP), disto-buccal (DB), disto-palatinal (DP). Mesial pit (mp): the deepest point of the mesial pit of the central fissure, as seen from the inside of the crown (black dot). b. Cusp point-landmarks and mesial pit, side view, model in transparency.

Lower panels: In total, 15 measurements per tooth were registered. All distances and angles were measured in 3D, i.e. the true lines connecting the landmarks were considered, not their 2D projection on the tooth's occlusal plane. c. Distance between cusps: distance between the cusp point-landmark of each cusp; every combination possible (n=6): D1: MP-MB, mesial cusps; D2: DP-DB, distal cusps; D3: MB-DP, diagonal cusps; D4: MP-DB, diagonal cusps; D5: MP-DP, palatinal cusps; D6: MB-DB, buccal cusps. d. Tooth depth: distance between the mesial pit and a plane throughout the highest cusp-point landmarks. e. Distance mesial pit to cusp point-landmark: distance between the mesial pit to the cusp point-landmark (n=4): d1: C-MB; d2: C-MP; d3: C-DB; d4: C-DP. f. Angles between cusps: angle between the lines traced from the mesial pit to each cusp point-landmark (n=4): a1: MP-MB; a2: MB-DB; a3: DB-DP; a4: DP-MP.

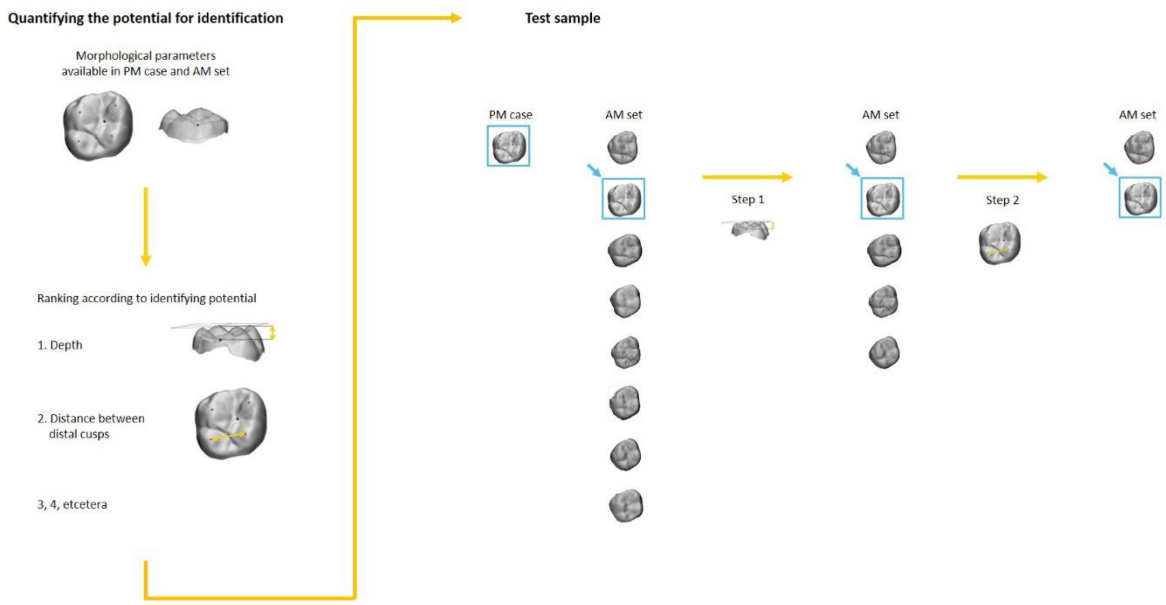

Fig. 4 Schematic representation of the practical implementation of the method displayed in Fig 1, according to the set-up in the current test sample. First, the morphological parameters available in the PM case and the AM set were measured on digitized upper first molar crowns. Second, the parameters were ranked according to their identifying potential. Note that we only show the univariate approach in this illustration.

A hypothetical scenario could be that we want to find the AM match of a PM case, in a set of eight AM cases. According to the ranking, the depth has the highest identifying potential, so we start with that (step 1). Five AM cases show a depth that is close to the one from the PM case. To further narrow down the AM set, we apply the next step (step 2) which is the distance between the distal cups. Two AM cases remain possible matches to the PM case. To find the exact match, further steps could be taken, be it univariate or multivariate, or other identification methods could be applied. Note that it is never guaranteed that the exact match can be found. Moreover, it cannot be excluded that the exact match is discarded in some stage of the process.