Imaging Science in Dentistry 2024; 54: 63-9
https://doi.org/10.5624/isd.20230218

Optimization of forensic identification through 3-dimensional imaging analysis of labial tooth surface using open-source software

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ABSTRACT

Purpose: The objective of this study was to determine the minimum number of teeth in the anterior dental arch that would yield accurate results for individual identification in forensic contexts.
Materials and Methods: The study involved the analysis of 28 sets of 3-dimensional (3D) point cloud data, focused on the labial surface of the anterior teeth. These datasets were superimposed within each group in both genuine and imposter pairs. Group A incorporated data from the right to the left central incisor, group B from the right to the left lateral incisor, and group C from the right to the left canine. A comprehensive analysis was conducted, including the evaluation of root mean square error (RMSE) values and the distances resulting from the superimposition of dental arch segments. All analyses were conducted using CloudCompare version 2.12.4 (Telecom ParisTech and R&D, Kyiv, Ukraine).
Results: The distances between genuine pairs in groups A, B, and C displayed an average range of 0.153 to 0.184 mm. In contrast, distances for imposter pairs ranged from 0.338 to 0.522 mm. RMSE values for genuine pairs showed an average range of 0.166 to 0.177, whereas those for imposter pairs ranged from 0.424 to 0.638. A statistically significant difference was observed between the distances of genuine and imposter pairs ($P < 0.05$).
Conclusion: The exceptional performance observed for the labial surfaces of anterior teeth underscores their potential as a dependable criterion for accurate 3D dental identification. This was achieved by assessing a minimum of 4 teeth.
(Imaging Sci Dent 2024; 54: 63-9)

KEY WORDS: Forensic Dentistry; Identity Recognition; Jurisprudence: Legal Identity: Imaging, Three-Dimensional

Introduction

In recent years, substantial advancements have been made in the application of 3-dimensional (3D) imaging methods for forensic identification. Forensic odontology has experienced a particularly notable surge in research, with a focus on the potential of 3D imaging techniques. Studies have covered a range of applications, including bite mark analysis, the precise quantification of morphological characteristics, and the identification of unique dental features.[1-4] The presence of distinctive attributes within the tooth structure confers a considerable benefit in human identification.[5-7]

The use of 3D imaging in forensic identification represents a transformative advancement, effectively addressing the limitations of 2-dimensional systems, which are susceptible to dimensional distortion. In dentistry, a variety of 3D imaging devices, particularly 3D intraoral scanners, have become widely adopted worldwide. These

Received September 27, 2023; Revised December 30, 2023; Accepted January 13, 2024
Published online February 22, 2024
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Imaging Science in Dentistry · pISSN 2233-7822 eISSN 2233-7830

scanners are primarily used to aid in patient diagnosis and treatment planning. As a result, 3D antemortem data of dental arches are now readily available through dental practitioners. Furthermore, the incorporation of 3D imaging techniques into forensic dental identification represents a comprehensive and holistic approach, enabling precise, interactive, and thorough documentation, visualization, and analysis of dental evidence.[8-10]

Evans et al. (2010)[11] determined that the Vivid 910 3D digitizer (Konica Minolta Sensing Inc., Osaka, Japan), which was also employed in the present study, effectively captures the surfaces of dental arches. The Vivid scanner has a well-documented history of use in both clinical and forensic settings, with applications that include monitoring changes in patients with cleft palates,[12] studying facial alterations,[13] and analyzing bite-mark evidence.[4,14] Previous research on the use of 3D imaging in forensic dental identification has primarily been focused on the comprehensive examination of entire tooth surfaces.[4,14,15] In contrast, the primary objective of this study was to precisely determine the minimum number of anterior teeth needed to distinguish an individual based on dental characteristics. Notably, this study utilized data acquired from the labial surfaces of the anterior teeth, which are easily accessible within the human dentition in many forensic contexts. This targeted approach employed a minimal tooth surface strategy to identify the most precise match of dental characteristics, both within an individual and between different individuals.

Materials and Methods

The design of the present study was reviewed and approved by the relevant institutional ethics committee under permit number 2017-3-17. A total of 14 dental casts were obtained from individuals who had provided their written informed consent to participate in the study. The eligibility criteria specified that participants must not have severe crowding, dental caries, or missing teeth in the anterior region. The maxillary dental casts underwent 2 scanning sessions using the Vivid 910 non-contact 3D digitizer (Konica Minolta Sensing Inc.). To ensure thorough 3D data acquisition for each participant, careful attention was paid to the placement of the dental casts on a rotating platform during the scanning process. This was particularly important for keeping the occlusal surface in an upright position. The dental casts were scanned from 6 different angles, with the assumption that each scanning cycle could capture a 60° field of view. In parallel, the transformation parameters, which included 3D rotation and translation, were meticulously calibrated within the 3D digitizer software. This step was crucial to achieve the highest possible level of accuracy in the scanning process.

The acquired 3D data were meticulously registered using Rapidform XOS/SCAN software (INUS Technology Inc, Seoul, South Korea). This registration process was implemented to enhance the accuracy of the data and to categorize scans into distinct groups. The criteria for grouping the 3D data for superimposition were as follows: group A consisted of data from the central incisor teeth on both the left and right sides; group B included data spanning from the right to the left lateral incisor; and group C contained data from the canines, also extending from the right to the left side (Fig. 1). The 3D data were segmented to determine the most effective number of teeth for differentiating between data from the same individual and those from different individuals. The term "genuine pair" referred to the superimposition of 2 separate 3D point cloud datasets from the same individual. Conversely, the term "imposter pair" applied when 2 separate 3D point cloud datasets from different participants were superimposed.

Subsequently, cloud-to-cloud (C2C) distances and root mean square error (RMSE) values were calculated by aligning 3D point cloud data for genuine and imposter pairs within each group using CloudCompare version 2.12.4 (Telecom ParisTech and R&D, Kyiv, Ukraine). The C2C distance is used to quantify the proximity between points in an analyzed point cloud by calculating the nearest neighbor distance. CloudCompare performs a search for the closest point in the reference cloud and then computes the Euclidean distance between the matched points. The RMSE was derived using the principles of the iterative closest point (ICP) algorithm, which serves to minimize the discrepancy between 2 sets of curves, surfaces, or 3D point clouds. The ICP algorithm holds 1 point cloud, designated as the reference or target, stationary while iteratively transforming the other, known as the source, to optimize its alignment with the reference. This transformation, which includes translation and rotation, is estimated iteratively to minimize an error metric, typically the sum of squared differences between the coordinates of matched pairs.[16] Low RMSE values indicate a high degree of similarity, signifying a close fit between the 3D point cloud model and the reference point cloud. In contrast, higher RMSE values correspond to greater discrepancies and less accurate similarity predictions. When comparing two 3D point clouds from the same individual, a lower RMSE value (approaching zero) suggests a closer alignment between the datasets.

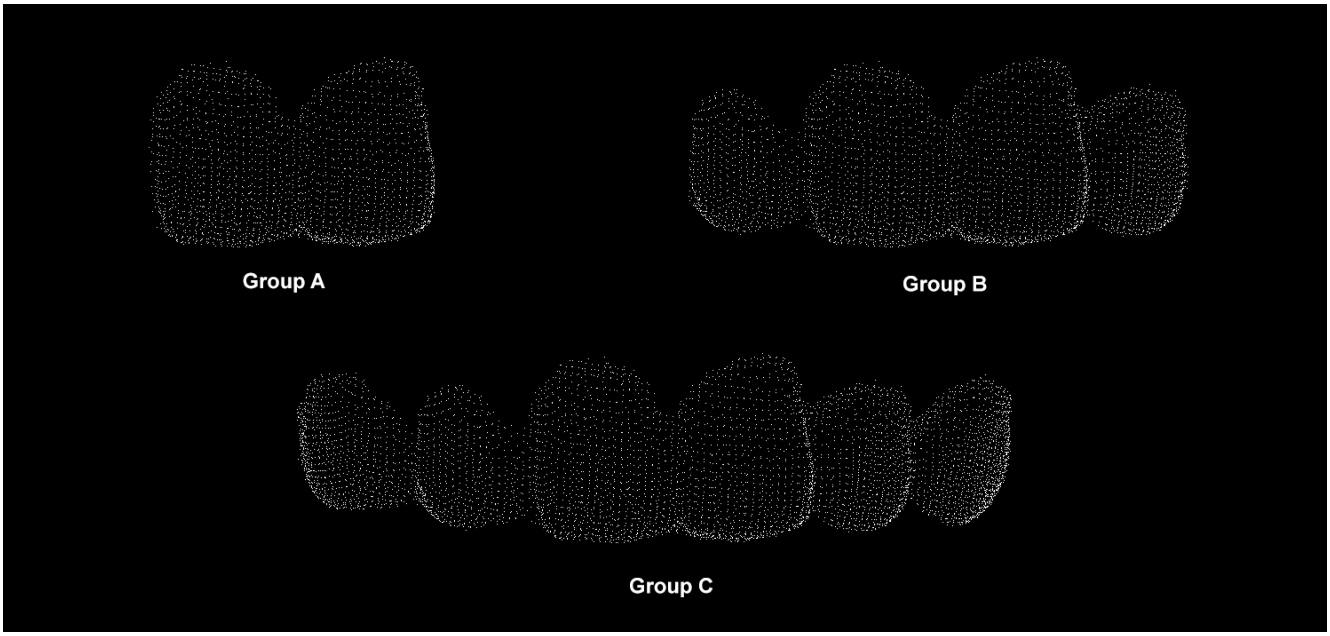

Fig. 1. Original 3-dimensional point cloud data of the labial surface for each study group. Group A included 3D point clouds of the right and left central incisors. Group B comprised 3D point clouds from the right to the left lateral incisor. Group C encompassed 3D point clouds from the right to the left canine.

Table 1. Distance and root mean square error (RMSE) values between point cloud datasets (C2C) for assessing the similarity of genuine and imposter pairs

Group	Pair	n	Distance		RMSE		*P*-value
			Mean	Range	Mean	Range	
A (2 teeth)	Genuine	14	0.153±0.028	0.105-0.214	0.166±0.024	0.116-0.205	<0.05
	Imposter	14	0.338±0.075	0.245-0.492	0.424±0.110	0.273-0.662	
B (4 teeth)	Genuine	14	0.160±0.027	0.108-0.189	0.177±0.029	0.118-0.210	<0.05
	Imposter	14	0.508±0.966	0.396-0.657	0.621±0.089	0.455-0.770	
C (6 teeth)	Genuine	14	0.184±0.032	0.122-0.256	0.176±0.029	0.119-0.209	<0.05
	Imposter	14	0.522±0.103	0.351-0.674	0.638±0.132	0.435-0.872	

C2C: cloud-to-cloud

The differentiation between 2 overlapping 3D point clouds was illustrated with a color map. The color scale ranges from blue to red, including green and yellow. In this gradient, blue represents the smallest distance value, while red indicates the largest distance measured between the superimposed 3D point clouds. The statistical significance of the differences between the genuine and imposter pairs was evaluated using SPSS version 23.0 (IBM Corp., Armonk, NY, USA).

Results

As shown in the descriptive analysis (Table 1), the mean C2C distance for the genuine pairs ranged from 0.153 to 0.184 mm. In contrast, the imposter pairs demonstrated C2C distances ranging from 0.338 to 0.522 mm. To assess the significance of these differences within each group, independent *t*-tests were performed. The results indicated a significant distinction between genuine and imposter pairs across all groups ($P<0.05$). The disparity in distance between genuine and imposter pairs was graphically depicted in color maps of the 3D data (Figs. 2 and 3). The color map for genuine pairs primarily displayed shades of blue and green, signifying minimal variation. In contrast, the color map for imposter pairs showed a wider range of

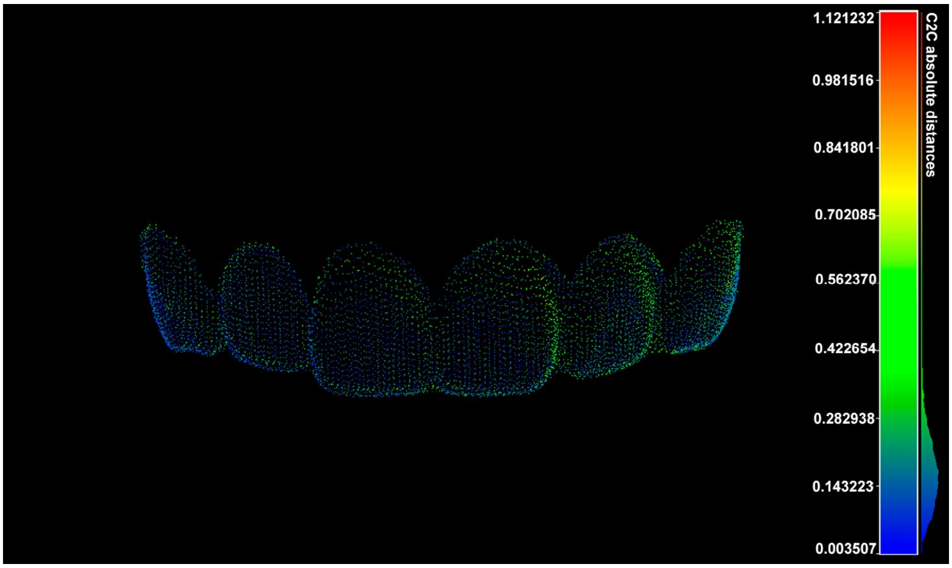

Fig. 2. Color map of 3-dimensional data for the genuine pair in group C, predominantly featuring shades of blue and green.

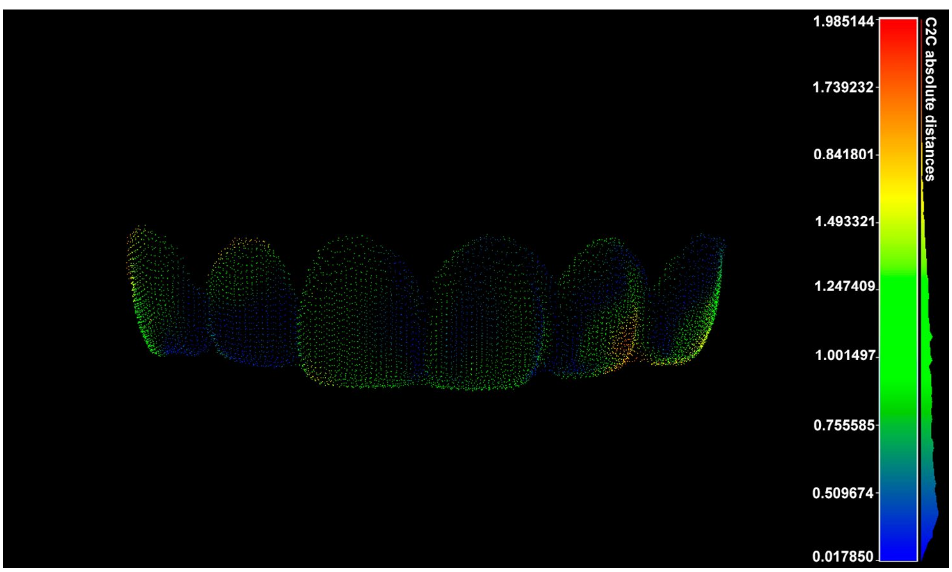

Fig. 3. Color map of 3-dimensional data for the imposter pair in group C, showcasing a gradient that spans from blue to red.

colors, spanning from blue to red, which reflects a greater degree of difference in distance compared to the genuine pairs.

The RMSE values for the genuine pairs of groups A, B, and C demonstrated an average range of 0.166 to 0.177. In comparison, the RMSE values for the imposter pairs varied from 0.424 to 0.638. To rigorously assess the differences in RMSE values between genuine and imposter pairs across various categories, a *post hoc* Bonferroni test was employed. This analysis indicated the absence of a statistically significant difference among the genuine pairs ($P>0.05$). However, a statistically significant difference was observed for the imposter pairs ($P<0.05$). This difference was particularly notable when comparing group A with group B, as well as group A with group C, as detailed in Table 2.

Discussion

A fundamental tenet of forensic odontology is the application of rigorous scientific methodology to the processing, examination, evaluation, and presentation of dental evidence in a legal context. Forensic sciences encompass 3 primary domains: civil or non-criminal legal matters, criminal cases, and research endeavors. A variety of techniques have been developed for dental identification, in the context of the effective management and presentation

Table 2. Comparison of the root mean square error values between groups A, B, and C for genuine and imposter pairs

Pair	Comparison to reference group	Absolute mean difference
Genuine	B to A	0.005±0.017
	C to A	0.006±0.017
	A to B	0.005±0.017
	C to B	0.001±0.017
	A to C	0.006±0.017
	B to C	0.001±0.017
Imposter	B to A	0.197±0.042*
	C to A	0.213±0.042*
	A to B	0.197±0.042*
	C to B	0.016±0.042
	A to C	0.213±0.042*
	B to C	0.016±0.042

*: $P<0.05$

of dental evidence in legal proceedings. These techniques rely heavily on the precision and accuracy of 3D imaging technologies. The progress made in 3D imaging holds considerable promise for improving the reliability and strength of dental evidence within the context of legal processes.[17-21]

Considerable attention has been given to the advancement of 3D imaging methodologies in the field of forensic identification. Notably, Evans et al. (2010) conducted a study investigating the use of 3D imaging techniques in forensic odontology.[11] Their research focused on 3D image analysis of bite marks, utilizing the MAVIS stereo-photogrammetric system and the Vivid 910 3D scanner. Building on this work, the present study also employed the Vivid 910 device and achieved noteworthy results, particularly in creating high-fidelity 3D images of dental casts. The findings of Evans et al. underscored the potential and effectiveness of the Vivid 910 scanner for 3D imaging in forensic dentistry, aligning with the goals of the present research.[4]

The primary objective of this study was to determine the number of anterior teeth required to obtain accurate results for forensic identification. To this end, dental casts displaying minimal dental crowding, caries, or missing teeth in the anterior region were carefully selected for inclusion in the research. The application of 3D data superimposition was restricted to the labial surfaces of the teeth, omitting the gingival mucosa. The gingival mucosa was deemed unsuitable for comparative analysis with existing data due to the confounding effects of gingivitis. This condition is known to cause both inflammatory and non-inflammatory shrinkage over time, which can be further aggravated by the excessive pressure applied during routine tooth brushing.[22,23] In contrast, teeth tend to maintain a relatively stable position and structure over short periods, barring the use of dental interventions. Consequently, they provide a more reliable basis for consistent data comparison.[5]

The results of this study revealed a significant difference between genuine and imposter pairs in all examined cohorts. However, a more detailed analysis using the *post hoc* Bonferroni test showed a statistically significant difference across groups, especially for the comparison of imposter pairs. This difference was particularly pronounced when comparing group A, which consisted of 2 teeth, with groups B and C, which included 4 and 6 teeth, respectively. The findings suggest that a distinct separation between genuine and imposter pairs becomes evident when the examination includes at least 4 labial surfaces of the anterior teeth.

The present study employed CloudCompare version 2.12.4, an open-source software tool designed for 3D point cloud and mesh processing, to overlay and analyze 3D point cloud data. CloudCompare was developed to enable direct comparisons between dense 3D point clouds. Its system is based on a custom octree structure, which is widely recognized for its efficacy in performing specialized tasks. Furthermore, CloudCompare was specifically designed to handle large point clouds, which became a key issue with the widespread adoption of terrestrial laser scanners for point cloud acquisition, often resulting in clouds containing upwards of 10 million points.[24]

CloudCompare has undergone numerous enhancements to expand its range of functionalities. The software's transformation process now allows for the assessment of point clouds relative to one another and in combination with a triangular mesh. A wide array of methods has been integrated to streamline the processing of point clouds. These include algorithms for registration, resampling, and the management of attributes like color, normal vectors, and scalar fields. The suite of capabilities has also grown to encompass statistical computations, sensor management, and both interactive and automatic segmentation. Furthermore, CloudCompare provides a variety of features to improve data visualization. The tools available include the creation of custom color ramps, efficient manipulation of color and normal vectors, effective management of calibrated photos, the use of OpenGL shaders, and support for extensible plugins.[24]

The fundamental principle of forensic identification is the comparative analysis of postmortem and antemortem data. The Interpol DVI Guide identifies 3 primary human identifiers: DNA analysis, fingerprints, and dental comparison.[25] Teeth are particularly valuable in forensic and anthropological contexts due to their uniqueness, durability, stability, and recoverability, along with the wealth of individual-specific information they contain.[5,18,26] Notably, 3D dental arch data, which can be obtained from a dental office, represent crucial antemortem information. Comparing these antemortem data with postmortem dental findings is a pivotal step in establishing the identity of a deceased individual. Furthermore, the use of 3D imaging technology is instrumental in expediting and enhancing the accuracy of victim and suspect identification in criminal cases. Digital scans of teeth allow for a 3D digital comparison of a suspect's teeth, eliminating any chance of distortion and enabling a comprehensive analysis in the investigation process.[27]

The identification of victims in forensic investigations presents a considerable challenge for forensic teams. In certain cases, inadequate preservation of the victim's intraoral state can hinder forensic dentists from determining the number of remaining teeth.[28] Additionally, it is crucial to acknowledge the difficulties in accessing the victim's oral cavity, particularly in instances of fatality. These challenges can create further impediments to the accurate documentation of intraoral data.[29] Under these circumstances, the labial surface of the anterior teeth is deemed the most accessible area of the oral cavity and offers sufficient information for individual identification.

In forensic identification, the registration, impression-taking, and acquisition of 3D data from the anterior teeth represent a practical and efficient method. This technique is applicable not only in cases of trismus but also when dealing with artificial crown coverage, intact dentition (sound teeth), and the need to minimize invasive dental autopsies in postmortem examinations. The natural curvature of the dental arch in anterior teeth provides an advantage when analyzing 3D data using the ICP algorithm, as it simplifies the alignment process between subjects. Even under challenging conditions, modern 3D imaging technologies enable the capture of 3D data of the labial surface of the anterior teeth, facilitating the extraction of extensive and precise data to bolster dental identification efforts.[30]

This study was primarily focused on comparing 3D data derived from dental casts. These casts sometimes exhibit rough surfaces, which may introduce noise and outliers, potentially impacting the accuracy of the research. In future studies, it will be crucial to investigate the acquisition of 3D data directly from the patient's oral cavity. This method is anticipated to yield a more accurate and direct representation of intraoral conditions, thereby mitigating the potential challenges posed by surface irregularities encountered with dental casts.

This study offers evidence supporting the effectiveness of using a minimum of 4 labial surfaces of the anterior teeth to differentiate between genuine and imposter pairs. This research successfully employed open-source 3D point cloud and mesh processing technologies, such as CloudCompare, to showcase the utility of these programs in forensic identification. Furthermore, the findings highlighted the importance of 3D imaging techniques in overcoming challenges related to less well-preserved intraoral conditions in forensic identification, especially in cases of restricted mouth opening.

Conflicts of Interest: None

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