Reliability of digital impressions for human identification based on palatal structures

Ph.D. thesis

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1. Introduction

In the event of a mass disaster, experts often face significant challenges in identifying the victims. Although there are established methods for identification, such as DNA analysis and fingerprinting, these techniques are not universally applicable because reference (antemortem) data may be absent. However, most patients have some form of dental records available. Consequently, dental identification is frequently the sole means of distinguishing dead bodies or human remains. The introduction of digital technology in dentistry has led to the development of new tools, such as intraoral scanners. A significant number of dentists are shifting from conventional impression techniques to digital scanning methods, thereby facilitating greater accessibility to digital antemortem data.

A large number of studies have characterized the anterior portion of the palate, especially the palatal rugae, as exhibiting distinct and persistent patterns that change minimally over time. Studies have shown that the palate and palatal rugae can be used for human identification. Simon et al. conducted a study comparing the palatal morphology of over 200 twins. They found that intraoral scanners could differentiate between monozygotic twins.

2. Objectives

Study 1: Reproducibility of the digital palate in forensic investigations: a two-year retrospective cohort study on twins

The aims of the study were:

1. to assess the effects of orthodontic treatment on forensic reproducibility
2. to assess the effect of comparison area selection (complete or anterior palate) on forensic reproducibility
3. to investigate the effect of the digitization method on forensic reproducibility (different scanners at different times)
4. to investigate the effect of the digitization method on technical reproducibility (different scanners at the same time)
5. to evaluate palatal stability by comparing differences between monozygotic twin siblings measured at the baseline and two years later.
6. to assess the discriminative potential of the palatal scans by comparing the forensic reproducibility of the individual subjects to the between-sibling difference

Study 2: Human identification via digital palatal scans: a machine learning validation pilot study

The aims of this study were:

1. to perform an external validation of a previously developed and published palatal geometry-based discrimination algorithm on a different population
2. to perform an external validation of a previously developed and published superimposition-based discrimination algorithm on a different population
3. to perform an external validation of a previously developed and published sex determination algorithm on a different population.

3. Methods

3.1. Study 1: „Reproducibility of the digital palate in forensic investigations: a two-year retrospective cohort study on twins”

3.1.1. Subject selection

In 2019, 20 sets of monozygotic twins (40 individuals) were initially scanned using five methods, representing simulated antemortem data. They were rescanned in 2021 to simulate postmortem data. Inclusion criteria required three error-free intraoral scans from 2019, age 18–32, and attending with their sibling. Exclusions included missing maxillary teeth (except second and third molars), orthodontic devices on the palate, or history of forced maxillary expansion. All procedures followed ethical guidelines, with informed consent and approval from the National Health Registration and Training Center (approval no. 36699–2/2018/EKU).

3.1.2. Palatal scanning

In 2019, all participants were scanned three times with an Emerald IOS (software v5.2.1, Planmeca), labeled as E. In 2021, they were rescanned using Emerald S (software v6.3.2.12 and 6.3.1.6) and Primescan (v5.1.3.7, Dentsply Sirona), labeled

ESA, ESB, and PS. Two indirect methods were also used: first, creating vinyl polysiloxane impressions (Virtual 380, Ivoclar) with a plastic tray, then digitized with a lab scanner (Planscanlab v5.0, Planmeca) as LAB. The impression was cast in Type IV dental plaster (Lean Rock, Whipmix), and the plaster model was scanned again to produce gypsum data (GYPS).

3.1.3. Data analysis

To compare two scans, they were superimposed using GOM Inspect® software (Suite 2020). The best-fit alignment was performed with the iterative closest point algorithm, minimizing total surface distances. The average of these distances is called the mean absolute distance (MAD).

3.1.4. Statistics

The effects of orthodontic treatment, comparison area (palate vs. anterior), and scanning technique on MAD were analyzed with a generalized linear mixed model (gamma distribution, log link). MAD differences between siblings with different scanners were tested using Kruskal-Wallis, with Bonferroni correction for multiple comparisons. All analyses were performed in SPSS v28.

3.2. Study 2: „Human identification via digital palatal scans: a machine learning validation pilot study”

This cross-sectional observational study was retrospectively registered on ClinicalTrials.gov (NCT05349942, 27/04/2022). Twenty-three postgraduate students from 11 countries in Asia and Europe, participated by providing anonymous scanned data. No specific inclusion or exclusion criteria were applied beyond consent, and participant selection was unaffected by investigators. The cohort simulated a real forensic scenario, such as a disaster situation. Participants included 16 females and 7 males, aged 23–35.

3.2.1. Scanning

Each participant had three scans using the Planmeca Emerald IOS (version 6.2.1.19), following a zigzag pattern from the incisive papilla. The countries' geographic coordinates were recorded, and differences between participants' locations were used to assess population diversity.

3.2.2. Measurement of the palatal vault geometry

Following Simon et al.'s guidelines, height, depth, and width were measured using GOM Inspect software.

3.2.3. Identification based on geometry

First, the absolute differences in height, depth, and width were calculated and square-rooted for normalization (sqrd_height, sqrd_depth, and sqrd_width). These values were then used in the two Fisher's linear discriminant functions developed from the training set. The following mathematical formula was used:

$Y_{identity} = 1.01 \times \text{sqrd\_height} + 1.00 \times \text{sqrd\_width} + 1.73 \times \text{sqrd\_depth} - 2.46.$

$Y_{stranger} = 3.59 \times \text{sqrd\_height} + 3.27 \times \text{sqrd\_width} + 3.65 \times \text{sqrd\_depth} - 9.23.$

3.2.4. Identification based on scan superimposition

Both scans were loaded into GOM Inspect® (Suite 2020) and cropped to focus on the incisive papilla and palatal rugae. They were then superimposed using the iterative closest point algorithm for best-fit alignment, minimizing the total surface distance. This minimized distance is referred to as MAD, as in Study 1.

3.2.5. *Sex determination based on geometry*

Fisher's linear discriminant functions for sex determination were previously developed using Caucasian twins. The next two functions compute discrimination scores for females and males. The formula used is:

$Y_{female} = 6.45 \times \text{height} + 5.56 \times \text{width} + 4.23 \times \text{depth} - 204$

$Y_{male} = 7.35 \times \text{height} + 5.91 \times \text{width} + 4.33 \times \text{depth} - 233$

3.2.6. *Statistical analysis*

In the geometric method, sensitivity, specificity, and accuracy were calculated from 1653 pairs, while in the superimposition method, MAD was analyzed for 253 pairs using multiple linear regression with longitude, latitude, and sex as variables. Sex determination accuracy was assessed with 58 pairs. Relationships between height, width, depth, and geographic variables were also analyzed via multiple regression. Results included 95% confidence intervals, and chi-square tests compared test and training sets, with $p<0.05$ indicating significance. All analyses were performed using SPSS Version 28.

4. Results

4.1. Study 1: „Reproducibility of the digital palate in forensic investigations: a two-year retrospective cohort study on twins"

4.1.1. The effect of orthodontic treatment and the comparison area on forensic reproducibility

Seventeen participants reported orthodontic treatment starting before 2019 or between 2019 and 2021, but no significant differences were found between treated and untreated groups ($p=0.777$), nor were there significant interactions with comparison area ($p=0.805$), scanning method ($p=0.158$), or all factors combined ($p=0.856$). Measurements of the anterior palatal region showed significantly better repeatability ($p<0.001$) and reproducibility across all combinations, so this area was used for subsequent analyses regardless of orthodontic treatment.

4.1.2. The effect of the digitization method on forensic and technical reproducibility

The Emerald S's technical reproducibility across software versions (ESB_ESA) was comparable to Emerald's repeatability (E_E). However, compared to Primescan (ESA_PS), it showed lower reproducibility, though still better than indirect digitization methods (ESA_LAB, ESA_GYPS). Overall, technical reproducibility and repeatability outperformed forensic reproducibility. Due to the lower reproducibility of indirect methods, only IOS-based techniques were used for further analysis.

4.1.3. Stability of the anterior palatal area over a two-year period

The median MAD in the anterior palatal region was 0.343 mm for Emerald (range 0.252–0.525 mm), 0.342 mm for Emerald S (range 0.239–0.577 mm), and 0.377 mm for Primescan (range 0.254–0.573 mm). No significant differences were observed (p=0.575).

4.1.4. The discriminative potential of anterior palatal scans using an IOS

Scans from 40 participants were matched with duplicates from the same scanner (E_E, repeatability), different scanners at the same time (ESA_ESB, ESA_PS, technical reproducibility), and different scanners at different times (E_ESA, E_ESB, E_PS, forensic reproducibility). A total of 240 pairs were created using IOSs (6 per participant), along with 60 sibling pairs. The smallest mean absolute distance (MAD) between siblings was 0.239 mm (see Fig. 5). Using this as a benchmark, 98.8% of the

240 replicates were correctly matched to the same individual. Three forensic reproducibility values overlapped with sibling comparisons, reducing accuracy. The maximum MAD for reproducibility was 0.141 mm after removing three measurements from the same individual.

4.2. Study 2: „Human identification via digital palatal scans: a machine learning validation pilot study”

4.2.1. Identification based on palatal geometry

The linear discriminant function using height, depth, and width achieved 91.2% sensitivity and 97.1% specificity in differentiating individuals from strangers, with no significant differences compared to previous data ($p=0.99$ and $p=0.058$). Overall accuracy was 97.1%. Logistic regression showed latitude and longitude had no effect on match accuracy, but matches between strangers of opposite sex were 5.4 times more likely to be correct ($p<0.001$).

4.2.2. Identification based on scan superimposition

Subject variability (0.214–1.068 mm) did not overlap with the repeatability range (0.011–0.093 mm). Sex had no significant effect on MAD (partial r = -0.06, p=0.343). Longitude showed a weak negative correlation with MAD (partial r = -0.16, p<0.01), and latitude was near significance (partial r = -0.12, p=0.058). Height correlated significantly with latitude (r=0.59), longitude (r=-0.46), and sex (r=0.71). Depth related to longitude (r=-0.32) and sex (r=0.31), but not latitude. Width was significantly influenced by sex (r=0.38); latitude and longitude had no significant effect.

4.2.3. Sex determination based on geometry

The discriminant function identified females more accurately than males, with a sensitivity of 69.0%, not significantly lower than the 82.2% in the Caucasian group (p=0.089). However, specificity was lower at 62.5%, significantly less than the 89.3% in the homogeneous population (p<0.05). Overall accuracy was 67.24%.

5. Conclusions

- The reproducibility of palatal scans obtained with different intraoral scanners is acceptable for human identification.
- The reproducibility remains acceptable after a two-year interval, regardless of the presence of non-surgical orthodontic treatment.
- Digitization of physical impressions made with stock trays or casts is unreliable for comparing palatal features.
- Intraoral scanning of the anterior palatal area (i.e., palatal rugae) demonstrates superior reproducibility, independent of the IOS brand.

- The palatal vault geometry- and the superimposition-based identification methods are good candidates for forensic feature comparison.
- The accuracy of machine learning based on palatal geometry is consistent across different populations.
- Sex can be determined from palatal geometry with moderate accuracy.

6. Bibliography of the candidate's publications

Publications related to the thesis:

Mikolicz A, Simon B, Gáspár O, Shahbazi A, Vag J. ***Reproducibility of the digital palate in forensic investigations: a two-year retrospective cohort study on twins.*** Journal of Dentistry. 2023 Aug;135:104562. doi: 10.1016/j.jdent.2023.104562. Epub 2023 May 24. PMID: 37230239.
Impact factor: 4.8 (ranking: D1)

Mikolicz Á, Simon B, Roudgari A, Shahbazi A, Vág J. ***Human identification via digital palatal scans: a machine learning validation pilot study.*** BMC Oral Health. 2024 Nov 14;24(1):1381. doi: 10.1186/s12903-024-05162-0. Erratum in: BMC Oral Health. 2024 Dec 23;24(1):1544. doi: 10.1186/s12903-024-05234-1. PMID: 39543590; PMCID: PMC11566520.
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Impact factor: 1.714 (ranking: Q2)

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Nagy Z, **Mikolicz A,** Vag J. ***In-vitro accuracy of a novel jaw-tracking technology***. Journal of Dentistry. 2023 Nov;138:104730. doi: 10.1016/j.jdent.2023.104730. Epub 2023 Sep 28. PMID: 37777084.
Impact factor: 4.8 (co-first author) (ranking: D1)

∑IF: 28,171