

Accuracy and Efficiency of Artificial Intelligence and Manual Virtual Segmentation for Generation of 3D Printed Tooth Replicas



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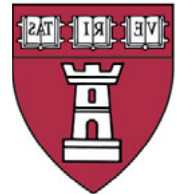
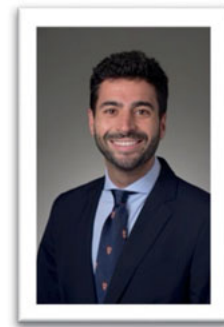
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ABSTRACT

Aims: The primary aim of this in vitro study was to compare methods for generating 3D-printed replicas through virtual segmentation, utilizing artificial intelligence (AI) or manual processes, by assessing accuracy in terms of volumetric and linear discrepancies. The secondary aims were the assessment of time efficiency with both segmentation methods, and the effect of post-processing on 3D-printed replicas.

Methods: Thirty teeth were scanned through Cone Beam Computed Tomography (CBCT), capturing the region of interest from human subjects. DICOM files underwent virtual segmentation through both AI and manual methods. Replicas were fabricated with a stereolithography 3D printer. After surface scanning of pre-processed replicas and extracted teeth, STL files were superimposed to compare linear and volumetric differences using the extracted teeth as the reference. Post-processed replicas were scanned to assess the effect of post-processing on linear and volumetric changes.

Results: AI-driven segmentation resulted in statistically significant mean linear and volumetric differences of -0.709mm (SD 0.491, $P < 0.001$) and -4.70%, respectively. Manual segmentation showed no statistically significant differences in mean linear, -0.463mm (SD 0.335, $P < 0.001$) and volumetric (-1.20%) measures. Comparing manual and AI-driven segmentations, AI-driven segmentation displayed mean linear and volumetric differences of -0.329mm (SD 0.566, $p = 0.003$) and -2.23%, respectively. Additionally, AI segmentation reduced the mean time by 21.8 minutes. When comparing post-processed to pre-processed replicas, there was a volumetric reduction of -4.53% and a mean linear difference of -0.151mm (SD 0.564, $p = 0.042$).

Conclusion: Both segmentation methods achieved acceptable accuracy, with manual segmentation slightly more accurate but AI-driven segmentation more time-efficient. Continuous improvement in AI offers the potential for increased accuracy, efficiency, and broader application in the future.

Keywords: Tooth Autotransplantation, Computer Aided Design, Digital Dentistry, Artificial Intelligence, 3D Printing, Stereolithography.

1. INTRODUCTION

Digital dentistry is a dynamic and rapidly evolving discipline that has revolutionized dentistry. One of its fundamental principles is the process of acquiring and accurately segmenting three-dimensional (3D) images (1). Virtual segmentation of Digital Imaging and Communications in Medicine (DICOM) data files obtained from Cone Beam Computed Tomography (CBCT) scans provides useful diagnostic tools for enhancing the accuracy and efficiency in dental implant placement, orthodontic planning, disease detection, and computer-aided rapid prototyping (CARP) for creating 3D tooth replicas (2-6). These CARP replicas may play an important role in therapeutic interventions such as tooth autotransplantation (7).

Tooth autotransplantation is a viable surgical-restorative alternative to replace a missing or non-restorable tooth by repositioning an autologous tooth within the same individual (7, 8). This treatment option is particularly well suited for patients under active alveolar process growth or those with malocclusions where the orthodontic movement of the transplanted tooth is indicated since a successfully transplanted tooth generally maintains a vital periodontium (9, 10). In the conventional autotransplantation technique, the extracted donor tooth was used to prepare the new recipient site (11). Also, is described in cases of severe periodontitis or teeth with a hopeless prognosis (12). This method required multiple fitting attempts and adjustments, increasing the risk of potential damage to the periodontal ligament of the future transplant (7, 8, 13). Additionally, these procedures prolong the time that the tooth remains outside the oral environment, risking the intervention's success (7).

In the contemporary autotransplantation technique, a 3D replica of the donor's tooth is fabricated based on the virtual segmentation of DICOM files from a previous CBCT scan. The 3D replica is then used as the template to create and adjust the recipient site, thus avoiding any damage to the donor's tooth and,

simultaneously, reducing the time the extracted tooth is out of the socket (8, 13, 14). The use of 3D replicas has demonstrated increased success and survival rates (7, 15-17). Nonetheless, to fabricate 3D replicas, it is crucial to establish an accurate method for CBCT virtual segmentation, which may be performed either manually or using artificial intelligence (AI) tools (1, 18). Manual segmentation relies on the operator's skill and experience, leading to longer segmentation time (1). AI-driven segmentation is fully automatic based on algorithms, offering a time-efficient alternative (1, 19, 20). However, it is yet unknown whether AI-driven CBCT segmentation provides the same accuracy as manual segmentation. Furthermore, post-processing protocols such as curing and support removal are known to induce dimensional changes due to material shrinkage, which may compromise the accuracy of the final replica in both linear and volumetric terms (21, 22).

Therefore, the primary aim of this study was to compare methods for generating 3D tooth replicas through virtual segmentation, utilizing either AI-driven or manual-driven methods. This comparison was accomplished by assessing the method's accuracy regarding volumetric and linear discrepancies. As secondary outcomes, the time spent during the tooth segmentation procedures with either method, and the effect of post-processing 3D tooth replicas were assessed. Previous studies have shown a statistically significant difference in linear and volumetric measurements when comparing replicas made with manual segmentation versus the original teeth (23). Therefore, given prior evidence of measurement discrepancies the null hypothesis of this investigation will be that no significant difference exists between methods - AI and manual-driven-.

2. MATERIALS AND METHODS:

2.1. Experimental design, setting, and timeframe.

This clinical investigation is in compliance with the Checking for Reporting In-Vitro studies (CRIS) (24). All the therapeutic and follow-up interventions in this study were carried out in the Specialization Postgraduate Implant Clinic of the XXX School of Dental Medicine between September 2021 and December 2023.

2.2. Ethical approval, patient recruitment, and extraction protocol

After obtaining approval from the Institutional Review Board (IRB21-1687), selected patients fulfilling the defined inclusion criteria were informed on the purpose of the study on their extracted teeth by one of the researchers (I.P., A.N.). Eligible patients included in this study signed the informed consent.

The inclusion criteria were: 1) The patient's ability to sign an informed consent form for enrollment in the study and 2) Any tooth suitable for extraction with a pre-operative CBCT scan taken no more than 60 days before the intervention. The exclusion criteria included teeth with carious lesions, cracked or fractured, presence of fixed dental prosthesis, endodontic treatment, or any restorative material that could cause scattering or might interfere with the CBCT virtual segmentation procedure.

All extractions were conducted as minimally traumatic as possible to avoid any damage to the tooth or adjacent anatomical structures. Following extractions, teeth were labeled and gently cleansed with water to remove any attached soft tissue and subsequently immersed for 30 min in a 1:10 solution of sodium hypochlorite for decontamination.

2.3. Sample preparation

2.3.1. CBCT acquisition and segmentation

Preoperative CBCT scans were obtained at XX School of Dental Medicine using the Veraview X800 MORITA device (MORITA Inc, Kyoto, Japan) for orthodontic, surgical or implant planning diagnosis. Standardized

settings were utilized for all CBCT scans, with an 80x40 field of view (FOV), 100 kV, 7 mA, and a resolution of 1.0 mm.

Manual segmentations were conducted by a single investigator (AN) following a standardized protocol. The CBCT scans were exported to the Blue-Sky Bio software (Blue Sky Bio, LLC, Libertyville, Illinois), and using the "Advanced Tooth Segmentation" tool of this software, segmentations were carried out in the area of interest. Teeth were manually outlined layer by layer using the lasso tool, and subsequent refinements were achieved utilizing the brush tool. Fifteen slices, with a minimum density grey values threshold of 900, and the "Smooth" function were applied to all manual segmentations. Then, the resulting 3D replicas were saved in standard tessellation language (STL) files (**Figure 1A**). AI-driven segmentations were carried out using the Diagnocat® software (Diagnocat, San Francisco, California) by a single investigator (I.P.). This software uses a Convolutional Neural Networks (CNN) algorithm following a progressive coarse-to-fine framework for resolution analysis. Then, the resulting 3D replicas were exported from Diagnocat® to STL files (**Figure 1B**).

2.3.2 3D printing

All 3D replicas were printed with a 3D printer (Formlabs Form 3B+, Formlabs, Somerville, Massachusetts), using Low Force Stereolithography (LFS) technology. Temporary crown-bridge (CB) resin (Formlabs, Somerville, Massachusetts) was used as the printing material. The pre-processed replicas underwent a thorough washing procedure in isopropyl alcohol for 3 minutes following manufacturer recommendations (**Figure 2**).

2.3.3 Post-processing

Following the manufacturer's recommendation, replicas with the supports still attached were first cured in the Form Cure (Formlabs, Somerville, Massachusetts) at 60°C (140°F) for 20 minutes. After the first curing, supports and rafts (3-5 supports, 0.70mm diameter, only on the occlusal surface) were manually

removed, and replicas were carefully post-processed per manufacturer's protocol. Finally, the replicas underwent a second curing process at 60°C (140°F) for 20 minutes.

2.3.4. Surface scanning

The extracted teeth and their corresponding 3D pre- and post-processed replicas were digitally scanned using a laboratory scanner (3Shape E4 Lab Scanner, 3Shape, Copenhagen, Denmark). The scanner was calibrated by conducting repeated measurements on 10 samples of known dimensions to validate the accuracy of the outcome. The teeth were secured on the scanner's platform by the root, and the coronal portion of each tooth was scanned first. Next, the teeth were inverted to scan the apical portion. The coronal and apical scans were then superimposed and aligned to create a complete 3D surface model of each tooth, which was then saved as an STL file.

An overview of the methodology can be found in **Figure 3 and 4**

2.4. Outcome measurements

2.4.1. Volumetric and linear assessment

For the volumetric measurements, STL files were analyzed by a single examiner (E.C.Q) using a previously published methodology with a specialized software package (Geomagic Control X, 3D Systems, Rock Hill, SC, USA), employing a best-fit surface mapping algorithm across three dimensions (25). This process employed the Iterative Closest Point (ICP) registration method, which iteratively minimizes the distance between corresponding points on the 3D surfaces to optimize spatial alignment. The entire projected volume was measured in mm³ (**Figures 5 and 6**). The examiner was trained and calibrated by conducting a series of 10 separate volumetric assessments in duplicate.

cliTo assess linear differences, STL files were exported to a software package (Autodesk Meshmixer, San Francisco, California), superimposed, aligned, and compared with the STL files from the extracted tooth. Alignments were refined through both automated registration and manual visual inspection. This dual-

step alignment strategy ensured high fidelity in the overlay, enhancing the reliability of subsequent quantitative comparisons. After calibration, the measurements, in mm along the X, Y, and Z axes, were carried out by a single examiner (A.N.) using the software's "Unit/Dimensions" analysis tool (**Figures 5 and 6**).

2.5. Statistical analysis

Sample size was calculated using SPSS v21.0 based on prior effect sizes, based on data from the study of Lee et al. 2022 (23), forecasting a mean difference of 0.38mm in linear measurements using 3D printed resin replicas (Formlabs®) (20) with a standard deviation of ± 0.22 for the mean linear measurement. Based on an alpha error of 5%, a power of 95%, and a two-sided (equivalence) test, 18 specimens were deemed necessary in this study.

Statistical analyses were done using each extracted tooth as the statistical unit. Outcome variables are presented through descriptive statistics, expressing continuous variables as means, standard deviations (SD), and confidence intervals of 95%, while categorical variables are expressed as percentages (%). Data normality was calculated using a Shapiro-Wilk test.

The primary outcome variable was the difference in volumetric changes between AI and manual segmentation of the final post-processed 3D printed replicas with the original extracted tooth, with either segmentation method used (i.e., manual or AI segmentation). Differences were compared using the 2-sided paired sample Student's T-test, with a p-value of $p \leq 0.05$ as statistically significant. When data did not meet normality criteria, a Wilcoxon signed-rank test was used. Binary categorical data were compared with a Chi-squared test. Intraclass correlation coefficients (ICCs) were also calculated for each of these comparisons to compare the correlation between the volumetric measurements of different protocols.

Secondary outcomes include efficiency between different segmentation methods; time was measured from the initial segmentation start to STL file export using a digital stopwatch. Also, volumetric and linear changes due to post-processing 3D replicas. Continuous variables used paired Student t-test or Wilcoxon signed-rank test depending on the normality of data, as well as ICCs. All data analyses were performed with SPSS version 21.0 software (Chicago, IL, USA).

3. RESULTS

3.1. Sample Characteristics

The final sample consisted of 30 extracted teeth from 8 patients (5 males and 3 females) with ages ranging between 13 to 55 years (mean age 32.3, SD 14.69). The extracted teeth comprised multi-rooted teeth (1 mandibular and 3 maxillary molars), and 26 were single-rooted teeth (15 premolars (7 mandibular and 8 maxillary), 4 canines (2 mandibular and 2 maxillary), 5 lateral incisors (2 mandibular and 3 maxillary), and two central incisors (1 mandibular and 1 maxillary) (Table 1).

3.2. Intra-examiner Reliability

The calibration exercise provided a high intra-examiner agreement, with a strong ICC ranging from 0.97 - 0.99 for the volumetric and linear analysis (Table 2).

3.3. Accuracy of the comprehensive Computer-Aided Rapid Prototyping (CARP) process using either manual segmentation or AI-driven segmentation

3.3.1 Linear measurements

A mean linear difference of 0.463mm (SD 0.335) was observed when comparing post-processed 3-D replicas obtained by manual segmentation with the corresponding extracted teeth. These differences were statistically significant ($p < 0.001$) (Table 3A).

Similarly, the mean linear difference when comparing post-processed 3-D replicas obtained by AI segmentation with the corresponding extracted teeth was 0.709mm (SD 0.491), with these differences being statistically significant ($p < 0.001$) (Table 3A).

Direct comparison between the 3D replicas obtained from manual and AI segmentation resulted in a mean linear difference of 0.221mm (SD 0.281). These differences were statistically significant ($p < 0.001$) (Table 3A).

3.3.2. Volumetric measurements

A mean volumetric difference of 5.651mm³ (SD 19.469) was obtained between the manually segmented 3D-printed replicas and the extracted teeth, corresponding to a 1.20% volume reduction. These differences, however, were not statistically significant ($p = 0.123$) (Table 3A and Table 4).

Conversely, the mean volumetric difference when comparing replicas obtained by AI segmentation with the corresponding extracted teeth was 22.128mm³ (SD 14.917), corresponding to a -4.70% volume reduction. These differences were statistically significant ($p < 0.001$) (Table 3A and Table 4).

Direct comparison between STL files (3D surfaces) generated from AI-driven and manual segmentation found an overall mean volumetric difference of 10.466mm^3 (SD 17.354, $p = 0.003$), equivalent to a -2.23% change in volume (Table 3A and Table 4). Replicas from AI-driven segmentation were smaller than those originating from manual segmentation

3.4. Accuracy of post-processed replicas in comparison to preprocessed replicas

Comparative analyses were conducted by separately comparing all the teeth replicas generated through AI-driven segmentation and manual segmentation, pre- and post-processing. Subsequently, data from all replicas were pooled together to assess the overall impact of post-processing on both volumetric and linear measurements.

3.4.1. Linear measurements

Analyzing the pre- and post-processed replicas from AI-driven segmentation showed a mean linear difference of 0.210mm (SD 0.777), demonstrating no statistical significance ($p=0.15$). In contrast, the same comparison for the manual segmentation counterpart group indicated a statistically significant mean linear difference of 0.093mm (SD 0.190, $p=0.012$). Combining both groups, an overall mean linear difference of 0.151mm (SD 0.564) was observed, and this difference was statistically significant ($p=0.042$) (Table 3B).

3.4.2. Volumetric measurements

When comparing the pre and post-processed replicas obtained from AI-driven segmentation, there was a mean volumetric difference of 21.419mm^3 (SD 6.523), -4.56% volume reduction. The same comparison for the replicas obtained from manual segmentation showed a mean volumetric difference of 21.975mm^3 (SD

7.232), -4.51% volume reduction. When both groups (AI and manually segmented) were pooled together, an overall mean volumetric difference of 21.697mm^3 (SD 6.833), -4.53% volume reduction, was found between pre-processed and post-processed replicas (Table.4). Importantly, all groups demonstrated statistically significant results ($p<0.001$) (Table.3B). Post-processed replicas were generally smaller than the pre-processed ones. (Figure 7)

3.5. Comparison of segmentation times between manual and AI-driven methods

The average time required for manual segmentation of 30 teeth was 23.97 minutes, and the average time required for AI-driven segmentation of the same teeth was reported to be 2.1 minutes.

4. DISCUSSION

The application of CARP in tooth autotransplantation involves multiple steps, which include CBCT acquisition and segmentation, 3D printing, and subsequent post-processing of 3D-printed replicas. The accuracy of each step may have a substantial impact on the overall accuracy of the final 3D replica. This study compares the entirety of the CARP process, assessing the accuracy of manual and AI tooth segmentation and its resulting 3D-printed replicas compared with the reference extracted teeth. The findings indicated that both methods were reliable and suitable for the fabrication of 3D tooth replicas, as the observed statistically significant differences between methods can be considered clinically

insignificant. However, time-efficiency analysis demonstrates a reduction in time of 21 minutes for the AI-driven method.

Manual segmentation is a well-established method to obtain tooth replicas, and previous studies have validated its accuracy (2). However, it is a time-consuming process that demands training and experience and relies on the interpretation skills of the operator. The average time for manual segmentation of each tooth in this investigation was 23.97 minutes. Nonetheless, other studies, such as Lee et al. (26), reported an average time of 15 minutes per tooth. Another study on manual segmentations of single and double-rooted teeth reported an average time of 6.6 minutes. Interestingly, AI-driven segmentation resulted in a 12.5-fold reduced time compared to manual segmentation (27). Considering that manual segmentation involves the investigator selecting and individually outlining multiple image slices, the reported time in different studies can vary significantly based on the type of teeth, the number of slices selected, and the precision of the outlining process (1, 26, 28). This fact was noted in this study considering the higher standard deviations in the manual vs. the AI method.

Several AI algorithms and deep learning models have recently been developed to carry out a fully automatic tooth segmentation more efficiently within a few minutes (1, 27, 29-31). One of the most effective models is Convolutional Neural Networks (CNN), which has been integrated into the software used for AI-driven segmentation in this study (1, 32). Comprising multilayer neural networks, CNN algorithms excel in identifying visual patterns quickly and with minimal pre-processing requirements (1, 32). However, these models have certain limitations, and recent review studies have underscored the necessity for validating their accuracy and reliability (1). Several challenges noted in other studies involve the segmentation of intricate root anatomy and apices, supernumerary and impacted teeth, especially third molars, and cases of crowding (1, 19, 27, 29, 33). These challenges may reasonably account for our

findings regarding the lower accuracy of AI-driven segmentation versus the manual segmentation group. This finding may also be explained by the fact that manual segmentation was performed by the same experienced operator under ideal and controlled circumstances.

This study demonstrated a reduction in volume (-0.38 to -2.6% for manual and AI segmentation, respectively) when comparing the virtual files obtained after segmentation, and the scanned tooth. Interestingly, volumetric and linear analyses of post-processed replicas showed a reduction trend compared to the extracted teeth (-4.53% volume reduction). These findings could be attributed to resin shrinkage during post-curing. Similarly, a study by Lee and Kim also reported that 3D replicas from CT images were generally smaller than the actual teeth (34). Their results revealed that, on average, the 3D images of donor teeth were -0.149 mm smaller than the actual teeth, and the 3D replicas were, on average, -0.067 mm smaller than their corresponding 3D images. Another study that observed a similar size discrepancy reported that the greatest differences between natural teeth and their replicas occurred at the tips of the premolars and the root furcation areas of molars; however, they suggested that deviations of less than 2.0 mm in these areas are unlikely to have clinical significance (35). Although the observed dimensional differences in this study may appear clinically acceptable, the authors recommend a 5% volumetric augmentation of the segmented tooth when using 3D-printed replicas for autotransplantation procedures. This is particularly advised in the apical and furcation regions of the root. In cases where the replica is not overcompensated, over-preparation of the recipient socket is recommended to facilitate proper fitting and reduce the risk of trauma during transplantation. This fact correspond to avoid any pressure over the root surface and to respect the cspace required for pDL. Recognizing the benefits of utilizing 3D replicas to reduce extraoral time and minimize damage to the periodontal ligament, the size discrepancy can be clinically manageable (7). This factor, coupled together with the volume reduction after virtual segmentation reported in this study, can be taken into consideration during the planning phase. Therefore, clinicians should be aware that the surgical area

should be minimally overprepared based on the 3D replica and to allow some physical space for blood clot formation and establishment around the roots of the autotransplanted tooth.

Another important aspect to consider is that, while this study reports AI-driven segmentation as less accurate than the manual method, it was notably more time-efficient and less dependent on operator input, demonstrated by a higher SD on the manual-segmentation group. Continuous advancements in AI algorithms and deep learning models hold the promise of significant improvements in tooth segmentation software. By understanding the potential for ongoing training and improvement of AI models, there is a clear path towards achieving higher accuracy and efficiency in digital segmentation processes. Efficiency is a significant factor in treatment planning and the practice of modern dentistry. In the context of autotransplantation procedures, earlier studies indicated that using 3D replicas can significantly enhance the success and efficiency of surgery. Shahbazian et al. and Verweij et al., reported extra-oral times of less than 1 minute when 3D replicas were employed and an overall significant reduction in procedural time (7, 8, 36, 37). If AI can streamline the treatment planning phase by reducing the time and effort required for tooth segmentation while maintaining an acceptable level of accuracy, it holds the potential to be a promising tool for enhancing the overall efficiency of surgical treatment planning.

As AI becomes more integrated into different dental software, understanding its potential applications and evaluating its effectiveness compared to traditional methods is essential (38). This knowledge allows dental professionals to gauge AI's strengths and limitations on accuracy, and workflow efficiency, enabling a more informed adoption of these technologies. The relevance of this investigation lies in a direct evaluation of the accuracy of AI-driven tooth segmentation, both in terms of volumetric and linear data. However, this study also presents some limitations that should be acknowledged. Firstly, the strict inclusion criteria and consistent use of the same CBCT machine, parameters, and standardized operator enhance the study's internal validity but also make it challenging to extrapolate these findings to other

protocols. Secondly, only one software for AI-driven segmentation has been tested, as well as 3D printing workflow, and the reported accuracy may not apply to other approaches utilizing different technologies.

Lastly, despite conducting a sample size calculation and achieving high power, this calculation was based on primary outcomes. Therefore, some secondary analyses may be underpowered, which may explain non-significant trends. Further studies with larger sample sizes are recommended to investigate the influence of multi-radicular teeth, furcation areas, and complex anatomy on the segmentation process, as well as the relationship between the time dedicated to manual segmentation and its final accuracy.

5. CONCLUSIONS

Within the limitations of this study, the following conclusions can be inferred:

1. AI-driven and manual virtual tooth segmentation methods are reliable and suitable for obtaining 3D tooth replicas.
2. AI-driven segmentation resulted in 3D replicas with reduced dimension than manual segmentation.
3. AI-driven tooth segmentation proved to be more time-efficient and independent of the operator's experience.
4. Post-processing of the 3D-printed tooth replicas consistently resulted in reduced dimensions.

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TABLES

Table 1. Sample characteristics

Total (Patients)	8 (%)
Male	5 (62.5)
Female	3 (37.5)
Age	
≤ 20	2 (25)
≤ 35	3 (37.5)
35-55	3 (37.5)
Total (Teeth)	30
Molar	4 (13.3)
Premolar	15 (50)
Canine	4 (13.3)
Lateral Incisor	5 (16.7)
Central Incisor	2 (6.7)
Number of Roots	
Multi (Three)	1 (3.3)
Multi (Two)	3 (10)
Single	26 (86.7)

Table 2. Intraclass correlation analysis of volumetric and linear measurements. (All comparisons were conducted using the STL files specific to each group.)

		Volumetric		Linear (Y)	
		ICC	p-value	ICC	p-value
Pair 1	Extracted Teeth	0.997	<.001	0.987	0.001
	Vs. Postprocessed Replicas from Manual Segmentation				
Pair 2	Extracted Teeth	0.994	<.001	0.971	0.003
	Vs. Postprocessed Replicas from AI Segmentation				
Pair 3	Extracted Teeth	0.997	<.001	0.995	<.001
	Vs. Manual Segmentation				
Pair 4	Extracted Teeth	0.998	<.001	0.975	<.001
	Vs. AI Segmentation				
Pair 5	AI Segmentation	0.997	<.001	0.983	<.001
	Vs. Manual Segmentation				
Pair 6	All Preprocessed Replicas (Manual & AI)	0.996	0.004	0.987	<.001
	Vs. All Postprocessed Replicas (Manual & AI)				

Table. 3. Comparative analysis of volumetric and linear measurements of STL files from virtual segmentation replicas

(A) AI-driven and manually driven analysis.

(B) Post-processed effect analysis

(A)

		Volumetric				Linear (Y)			
		Mean	SD	95% CI	p-value	Mean	SD	95% CI	p-value
Pair 1	Extracted Teeth	5.651	19.469	[-1.62, 12.92]	0.123	0.463	0.335	[0.34, 0.59]	<.001
	Vs. Postprocessed Replicas from Manual Segmentation								
Pair 2	Extracted Teeth	22.128	14.917	[16.56, 27.70]	<.001	0.709	0.491	[0.53, 0.89]	<.001
	Vs. Postprocessed Replicas from AI Segmentation								
Pair 3	Extracted Teeth	1.766	0.566	[-5.84, 9.37]	0.638	0.221	0.281	[0.12, 0.33]	<.001
	Vs. Manual Segmentation								
Pair 4	Extracted Teeth	12.232	11.334	[7.99, 16.46]	<.001	0.550	0.574	[0.34, 0.76]	<.001
	Vs. AI Segmentation								
Pair 5	AI Segmentation	10.466	17.354	[3.99, 16.95]	0.003	0.329	0.566	[0.12, 0.54]	0.003
	Vs. Manual Segmentation								

(B)

		Volumetric				Linear (Y)			
		Mean	SD	95% CI	p-value	Mean	SD	95% CI	p-value
Pair 1	Preprocessed Replicas from AI Segmentation	21.419	6.523	[18.98, 23.85]	<.001	0.210	0.777	[-.008, 0.50]	0.150
	Vs. Postprocessed Replicas from AI Segmentation								
Pair 2	Preprocessed Replicas from Manual Segmentation	21.975	7.232	[19.27, 24.68]	<.001	0.093	0.190	[0.02, 0.16]	0.012
	Vs. Postprocessed Replicas from Manual Segmentation								
Pair 3	All Preprocessed Replicas (Manual & AI)	21.697	6.833	[19.93, 23.46]	<.001	0.151	0.564	[0.01, 0.30]	0.042
	Vs. All Postprocessed Replicas (Manual & AI)								

Table.4. Descriptive volumetric comparison.

Comparisons for pairs 1, 2, 4, and 5 were conducted by establishing the extracted teeth as a reference for comparing the size of the replicas. In the case of pair 3, AI-segmented 3D replicas were compared against manually segmented replicas, with the manual group serving as the reference. For all post-processing groups, pre-processed replicas were used as the reference for comparison.

** “Segmentation manual” and “Segmentation AI” are digital files (STL) that have yet to be printed.

** “Pre-processed” and “Post-processed” represent digital files (STL) obtained after scanning the 3D-printed replicas.

		Volumetric		
		Mean	Mean diff	% diff in Vol
Pair 1	Extracted Teeth	470.782	5.651	-1.20
	Vs. Postprocessed Replicas from Manual Segmentation	465.132		
Pair 2	Extracted Teeth	470.782	22.128	-4.70
	Vs. Postprocessed Replicas from AI Segmentation	448.654		
Pair 3	Extracted Teeth	470.782	1.766	-0.38
	Vs. Manual Segmentation	469.016		
Pair 4	Extracted Teeth	470.782	12.232	-2.60
	Vs. AI Segmentation	458.550		
Pair 5	AI Segmentation	458.550	10.466	-2.23
	Vs. Manual Segmentation	469.016		

Volumetric				
		Mean	Mean diff	% diff in Vol
Pair 1	Preprocessed Replicas from AI Segmentation	470.073	21.419	-4.56
	Vs. Postprocessed Replicas from AI Segmentation	448.654		
Pair 2	Preprocessed Replicas from Manual Segmentation	487.107	21.975	-4.51
	Vs. Postprocessed Replicas from Manual Segmentation	465.132		
Pair 3	All Preprocessed Replicas (Manual & AI)	478.590	21.697	-4.53
	Vs. All Postprocessed Replicas (Manual & AI)	456.893		

FIGURES

Figure 1. A, Example of some steps for manual virtual segmentation of a tooth from CBCT file.

B, Example of the same CBCT after AI-driven automated segmentation, opened in a CAD software (Meshmixer®)

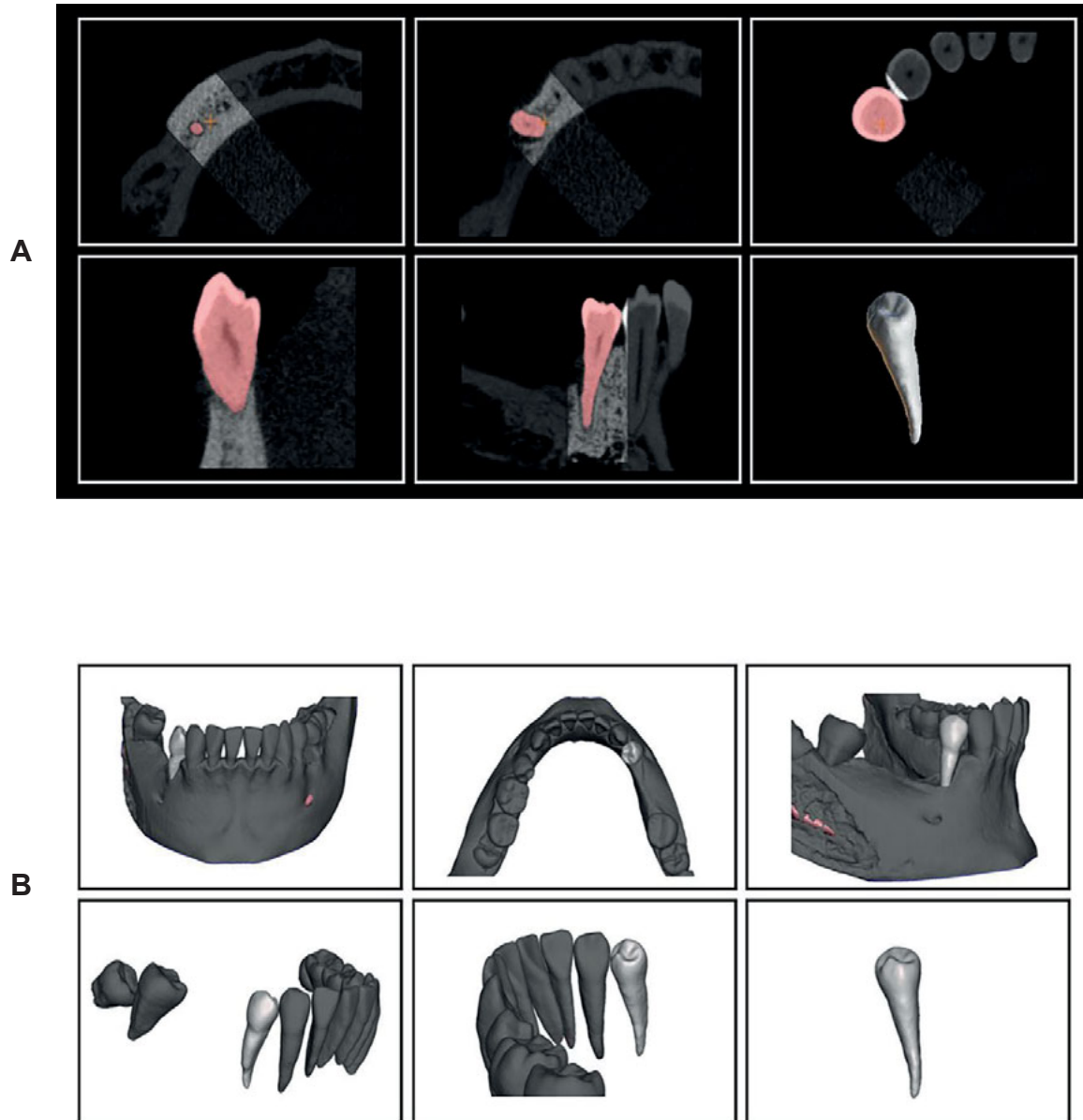


Figure 2. Side-by-side views of the extracted tooth (A) next to its corresponding 3D printed replica from IA virtual segmentation (B).

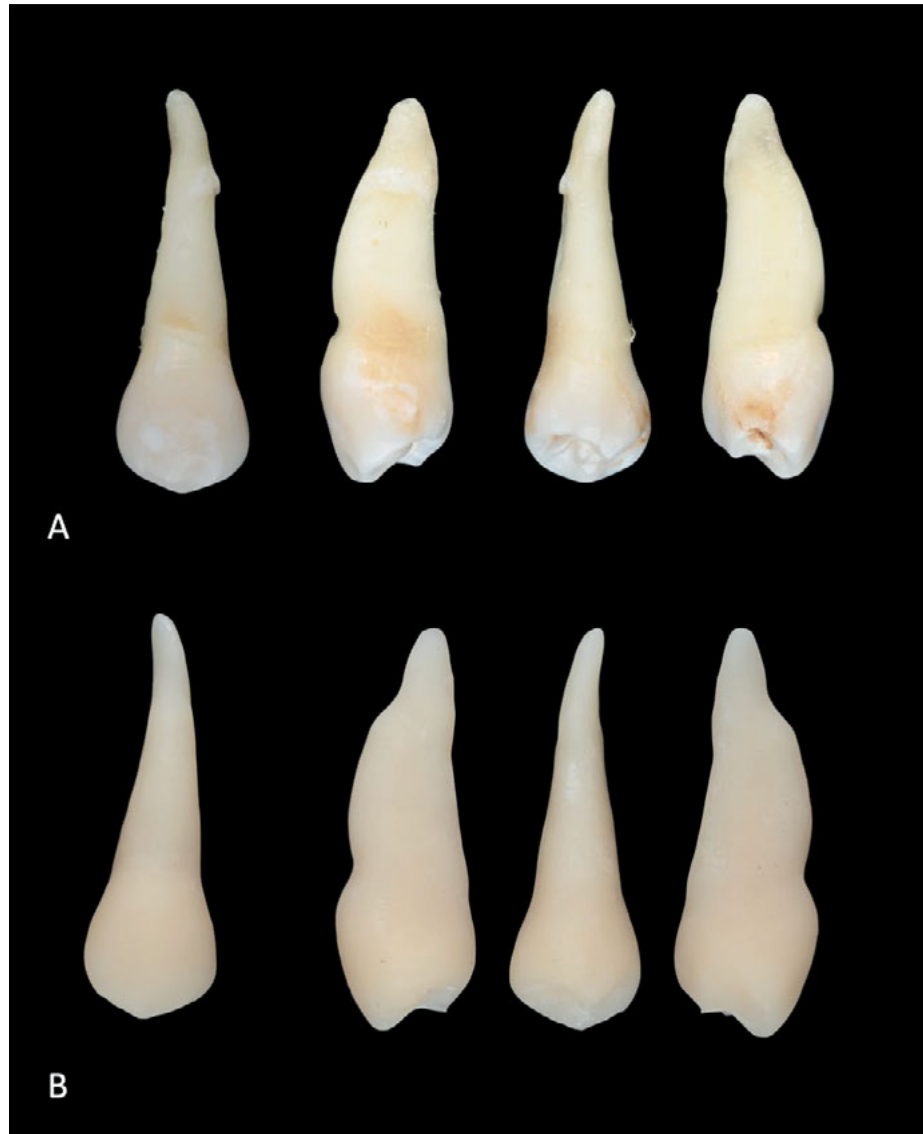
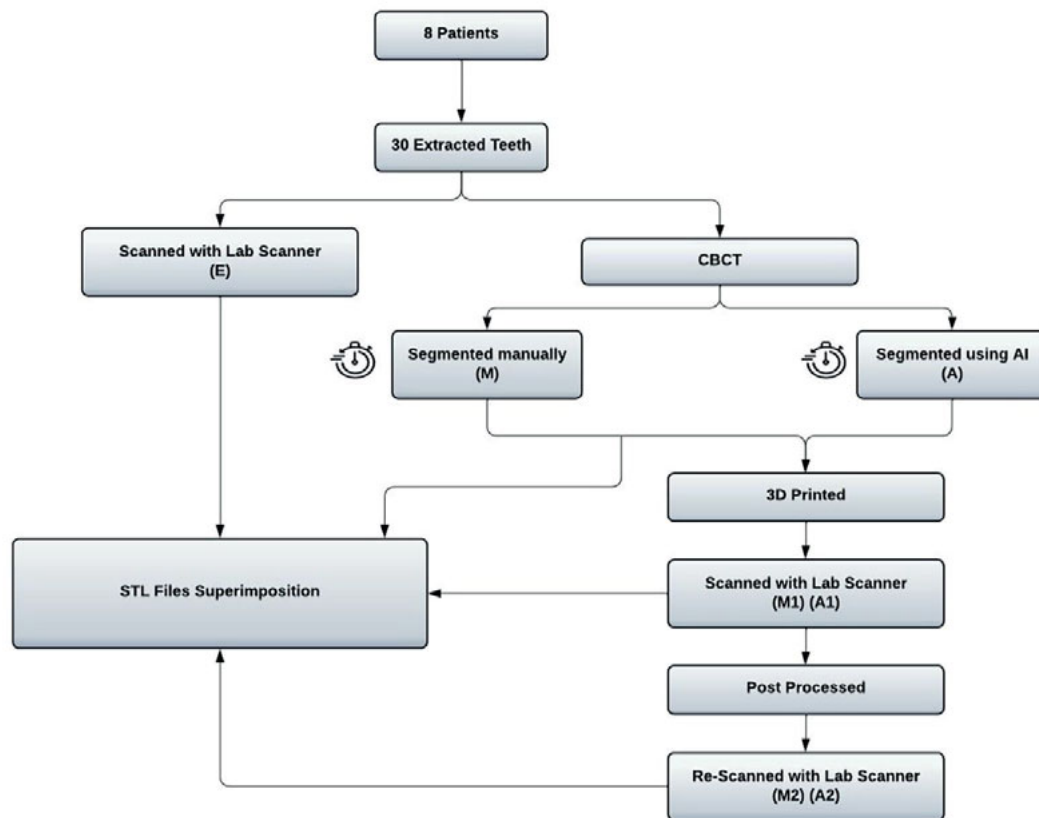


Figure 3. Summary of methodology. Using the obtained STL files, comparisons were made between E vs M, E vs A, E vs M2, E vs A2, and M vs A groups to assess segmentation accuracy; and effect of post-processing was assessed with comparisons between M1 vs M2 and A1 vs A2 groups.

*Time required for both manual and AI segmentation was recorded.

**All CBCT scans were taken prior to the extractions and samples were scanned after extraction.



STL Files:

- Extracted Teeth (E)
- Manual Segmentation (M)
- AI Segmentation (A)
- Pre-processed Manual Segmentation (M1)
- Pre-processed AI Segmentation (A1)
- Post-processed Manual Segmentation (M2)
- Post-processed AI Segmentation (A2)

Figure 4: Photo representation of the comparison among natural teeth, virtual segmented files and 3D printed tooth replicas

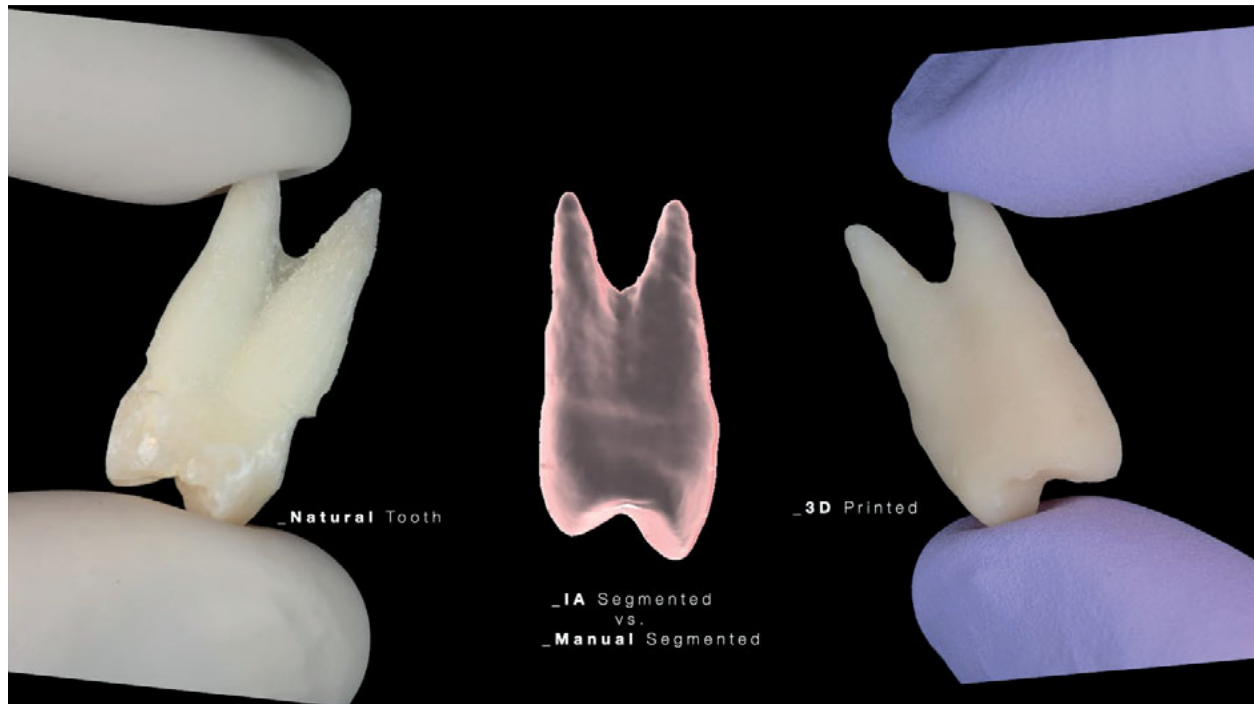


Figure 5. A, Paired superimposition of the STL files showing discrepancies between files as represented by 3D comparison color-map. B, Paired superimposition of the STL files for linear analysis.

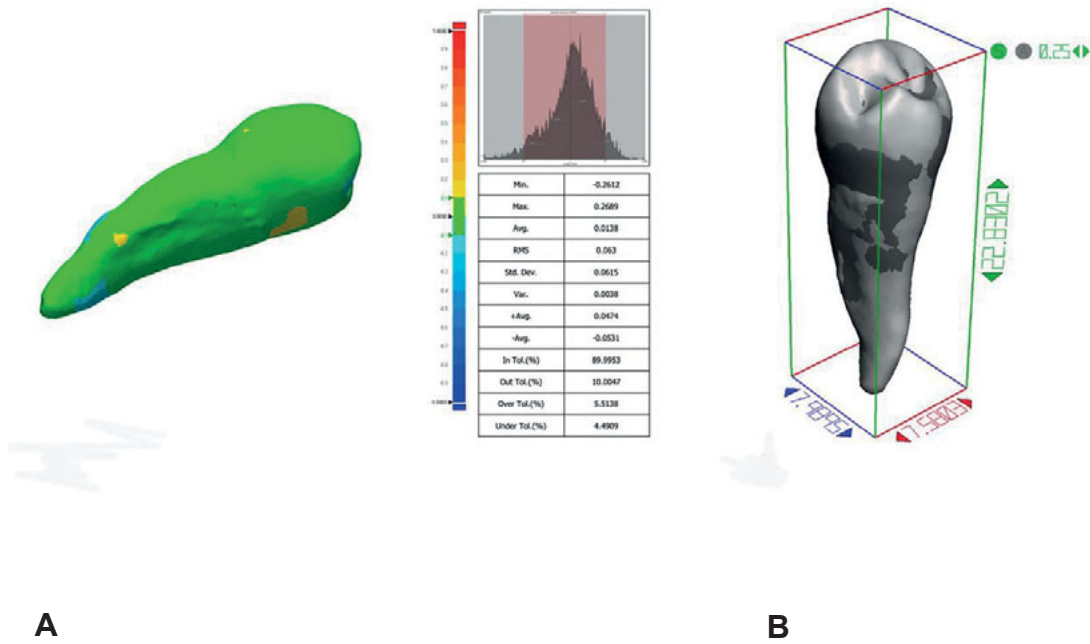
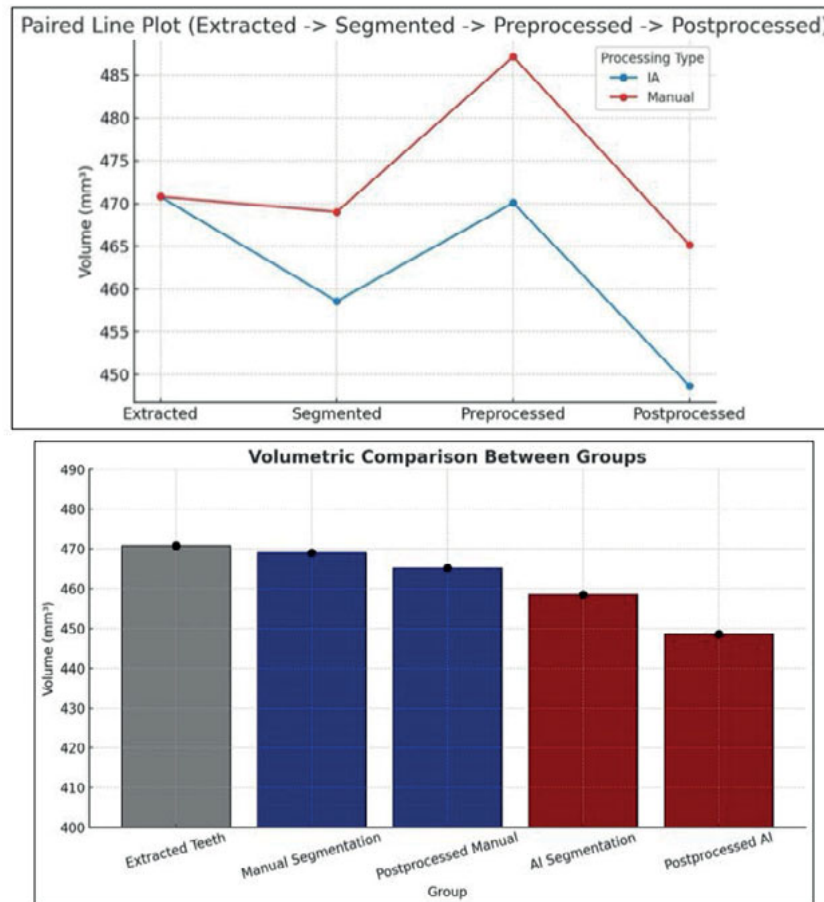


Figure. 6. Example of the methodology followed. Left: AI segmentation analysis and Right: manual segmentation analysis. Each row, from left to right: Geomagic superimposition for volumetric analysis (3D color map comparison); Meshmixer superimposition for linear analysis (dark grey); SLT file of extraorally scanned tooth; STL file of (AI or Manual) segmented tooth.

View	Extracted Tooth vs AI Segmentation				View	Extracted Tooth vs Manual Segmentation			
	Volumetric	Linear	Tooth	3D Replica		Volumetric	Linear	Tooth	3D Replica
Buccal					Buccal				
Lingual					Lingual				
Mesial					Mesial				
Distal					Distal				

Figure 7: Volumetric comparison between original extracted teeth and replicas generated through manual and AI-driven segmentation, across processing stages. (Top) Paired line plot showing individual trends from extracted to post-processed volumes. (Bottom) Bar chart summarizing mean volumes per group, indicating consistent volume reduction after post-processing



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