ORIGINAL ARTICLE

AJO-DO

Reliability and reproducibility of a best-fit superimposition method for digital models of adult patients treated without extractions

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Introduction: Cone-beam computed tomography (CBCT) is considered the gold standard for 3-dimensional superimposition in assessing tooth movement during orthodontic treatment. However, given current guidelines emphasizing the reduction of radiation exposure, this study aimed to evaluate the accuracy, reliability, and reproducibility of a digital model superimposition technique that does not require CBCT. **Methods:** This retrospective study included 10 adult patients who underwent comprehensive orthodontic treatment without extractions. All patients had full-head CBCT scans and corresponding maxillary and mandibular digital dental models. Two evaluators assessed tooth movement using a new superimposition technique based on Standard Triangle Language files, using the palatal rugae as a superimposition reference for the maxillary arch and the transfer of the mandibular position through the interarch occlusal relationship. The accuracy of this method was compared with that of a CBCT-based reference workflow involving the integration of scanned dental models into CBCT images. **Results:** The mean variation in reference landmark positions across the 3 spatial planes was similar between the methods for both arches. Interevaluator differences (Δ) ranged from –0.07 to 0.06 mm, which were not considered clinically significant. Student *t* tests showed no statistically significant differences between evaluators for any axis in either method ($P > 0.05$). Intraclass correlation coefficients demonstrated high agreement between the 2 methods, ranging from 0.88 to 0.98. **Conclusions:** The 3-dimensional digital model superimposition technique using the palatal rugae for the maxillary arch and the interarch occlusal relationship for the mandibular arch is a reliable and reproducible alternative to CBCT-based methods for evaluating orthodontic tooth movement in nongrowing patients treated without extractions. (Am J Orthod Dentofacial Orthop 2026;■:■-■)

In orthodontics, superimposition techniques have been commonly used by both researchers and clinicians to measure growth modifications and tooth movements, as well as to assess treatment outcomes. Traditionally, these assessments have relied on the superimposition of serial cephalometric radiographs registered on stable skeletal structures, such as the cranial base, maxilla, or mandible.[1] However, this 2-dimensional (2D) method has significant limitations, including image distortion and the inability to accurately capture 3-dimensional (3D) changes in all planes of space.[1-3] Cone-beam computed tomography (CBCT) has addressed many of these limitations and is now regarded as the gold standard for 3D assessment of

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The data that support the findings of this study are available upon request from the corresponding author.
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complex dentofacial structures.[4] CBCT allows for the acquisition of high-resolution skeletal imaging and the 3D reconstruction of maxillary and mandibular bones, enabling volumetric visualization of oral and maxillofacial anatomy with a high degree of accuracy and detail.[4-6]

Serial CBCT voxel-based superimposition on the cranial base has been proposed as a reliable reference for evaluating facial growth and orthodontic treatment outcomes because it provides a stable skeletal framework for comparison.[7] The integration of scanned dental models into CBCT images has been proposed to overcome the limited representation of dental crowns in CBCT datasets. In this approach, digital models in the Standard Triangle Language (STL) format are incorporated into CBCT volumes, and the accuracy of this registration increases when a broad dental surface is used.[8] This method is not, by itself, the reference standard but rather an adjunctive procedure that enables reliable evaluation of occlusal relationships and detailed crown morphology while maintaining the stable skeletal reference, facilitating dental landmark identification.

However, the CBCT superimposition approach requires full-skull imaging and, in accordance with the ALARA principle (As Low As Reasonably Achievable), efforts must be made to minimize radiation exposure. Consequently, current guidelines recommend against the routine use of CBCT in conventional orthodontic practice.[9] Given these radiation concerns, the development of a reliable, radiation-free method for evaluating treatment outcomes is imperative for routine clinical use.

Intraoral scanning offers a noninvasive means of obtaining full-arch digital dental models, facilitating accurate diagnosis, treatment planning, and progress monitoring.[2,3,10] Superimposition of 3D digital models using either landmark-based or surface-based registration techniques enables precise analysis of tooth movement and arch dimensional changes in all 3 spatial planes without the need for radiation.[3,11,12] Compared with 2D cephalometric superimposition, this digital method provides several advantages, such as the elimination of tracing errors, accurate size representation, absence of image distortion, and radiation-free assessment.[12] Consequently, numerous studies have explored various methods for applying 3D model superimposition in orthodontics.[1-3,6,11,13-22]

Successful superimposition of digital models before and after treatment requires the identification of stable reference regions.[3,18] For maxillary models, the medial two-thirds of the third ruga and the posterior area along the midpalatal suture have been proposed as stable reference structures because they undergo the least changes during treatment, and the palatal mucosa in this area undergoes minimal deformation during impression due to the immovable soft tissues.[1,2,6,11,19,20] However, a recent systematic review highlighted the scarcity of evidence supporting reference areas for mandibular digital model superimposition.[12]

An et al[3] evaluated the use of alveolar bone surfaces as reference regions for 3D mandibular model superimposition and reported unsatisfactory results in patients without mandibular tori, especially when the lingual alveolar surfaces of the anterior teeth were included, with discrepancies ranging from 1.5-10 mm when compared with cephalometric measurements. Park et al[6] proposed a method combining 3D CBCT images and digital models, suggesting that the best-fit method on the basal bone surface of the mandible, which is unaltered by orthodontic treatment, offers a reliable, reproducible, and straightforward reference for mandibular arch superimposition, despite requiring the use of radiation to be performed.

To date, 1 study has attempted to validate a mandibular model superimposition technique without CBCT. Souza et al[21] presented a step-by-step protocol for 3D model superimposition of both arches using a single reference point defined within the Universal Coordinate System: the palatal rugae region for the maxilla and the lingual mucogingival junction for the mandible. However, because the study did not compare the method with a reference standard, such as CBCT-based superimpositions, its accuracy was not assessed.

Given the growing demand for radiation-free assessment methods and the lack of validated stable structures for digital model superimposition, the aim of the present study was to evaluate the accuracy, reliability, and reproducibility of a digital model superimposition technique using palatal rugae-based registration for the maxillary arch and the transfer of the mandibular position through the interarch occlusal relationship, compared with a CBCT-based reference workflow involving the integration of scanned dental models into CBCT images.

MATERIAL AND METHODS

This retrospective study included a sample of 10 patients (2 males and 8 females) with a mean age of 26 years at the beginning (range, 20-29 years) and 28 years (range, 22-32 years) at the end of treatment. All patients underwent comprehensive nonextraction orthodontic treatment between 2016 and 2021. Inclusion criteria were complete permanent dentition, skeletal maturity at cervical vertebral maturation stage CS6[23] at

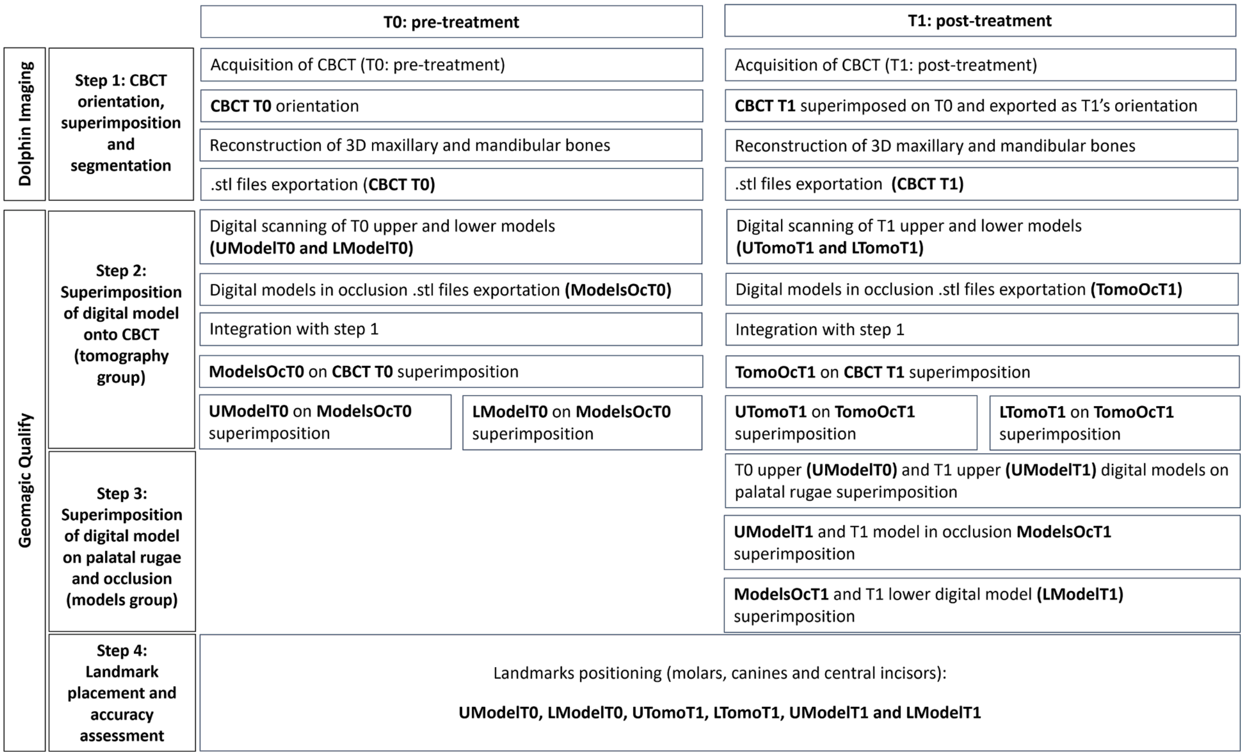

Fig 1. Flowchart illustrating the 4 main steps of the superimposition method. Step 1 was performed using Dolphin Imaging, whereas steps 2-4 were completed using Geomagic Qualify software.

pretreatment, and availability of full-head CBCT scans and maxillary and mandibular dental casts at pretreatment (T0) and posttreatment (T1).

Each dental cast was scanned separately and in occlusion with the intraoral scanner iTero Element 2 (Align Technologies, San Jose, Calif) and exported in STL. The digital casts were analyzed using a specific software (Geomagic Qualify 2013.0.1:64 Bit Edition program, Raindrop Geomagic, Inc, Cary, NC).

The superimposition method consisted of the following 4 main steps (Fig 1):

1 CBCT orientation, superimposition, and segmentation
2 Superimposition of digital models onto CBCT
3 Superimposition of digital models on the palatal rugae and the interarch occlusal relationship
4 Landmark placement and accuracy assessment

The digital datasets and abbreviations used in the study are shown in the schematic illustration in Figure 2.

Full head 3D CBCT image data were acquired with a Kodak K9500 cone-beam scanner (Carestream Health, Rochester, NY). All patients underwent CBCT scanning in maximum intercuspation, in facial mode (field of view, 20 × 18 cm) with a 0.2 mm isotropic voxel, an exposure time of 10.8 seconds, 90 kVp, and 10 mA. The reconstructed digital data were downloaded as Digital Imaging and Communications in Medicine (DICOM) files. Both pre- and posttreatment (T0 and T1) DICOM data were uploaded to the Dolphin Imaging program (Dolphin International, Chatsworth, Calif), and CBCT T0 was oriented according to the Frankfort plane (Fig 3, *A*). As the patients examined in our sample were nongrowing subjects, each CBCT T1 was superimposed on CBCT T0 using Dolphin Imaging's voxel-based image registration on the cranial base (Fig 3, *B* and *C*). Then, the threshold was visually adjusted to ensure adequate reproduction of the crowns of the maxillary and mandibular teeth, allowing the segmentation of the maxillary and mandibular jaws from the CBCT scans and their export as single STL files, named CBCT T0 and CBCT T1 (Fig 3, *D*).

T0 and T1 digital models in occlusion, designated ModelsOcT0 and TomoOcT1, respectively, were superimposed onto their corresponding CBCTs (CBCT T0 and CBCT T1) through the best-fit alignment according to Noh et al.[8] To maximize the common surface

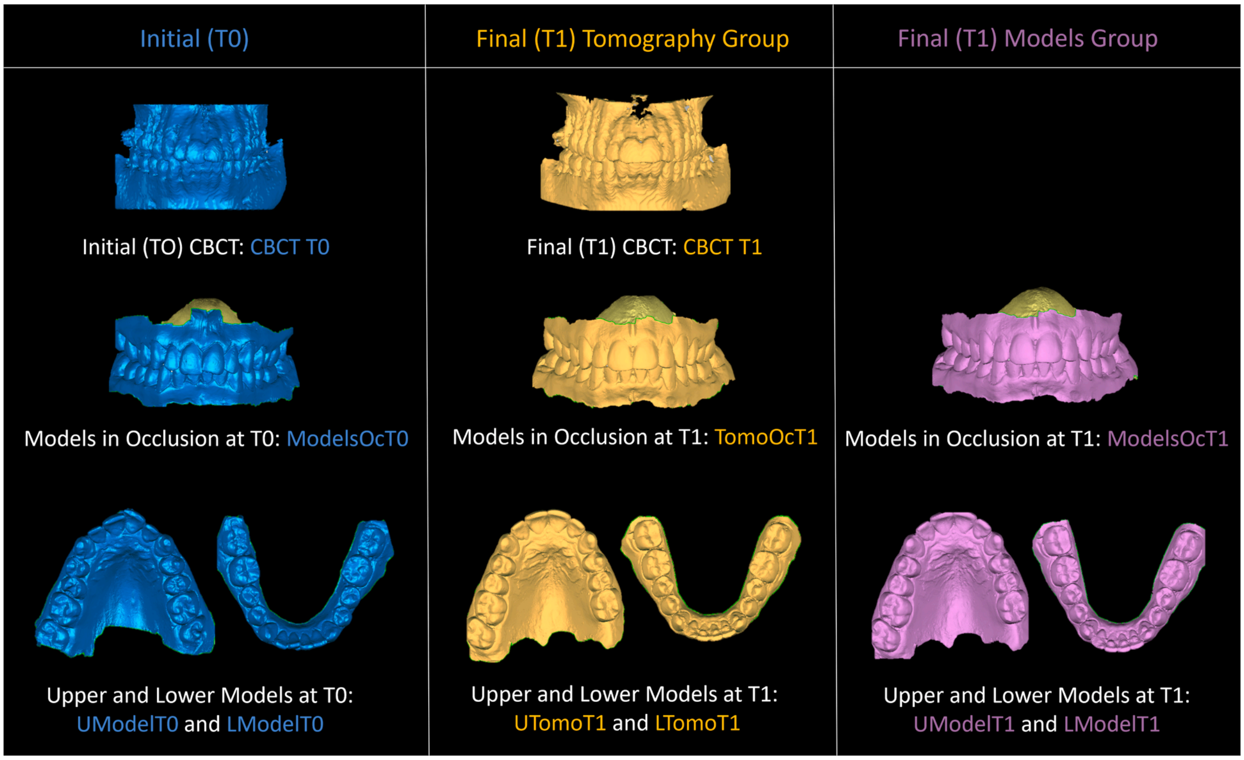

Fig 2. Schematic illustration of the digital datasets and abbreviations used in the study at pre- (T0) and posttreatment (T1) for the tomography and models groups.

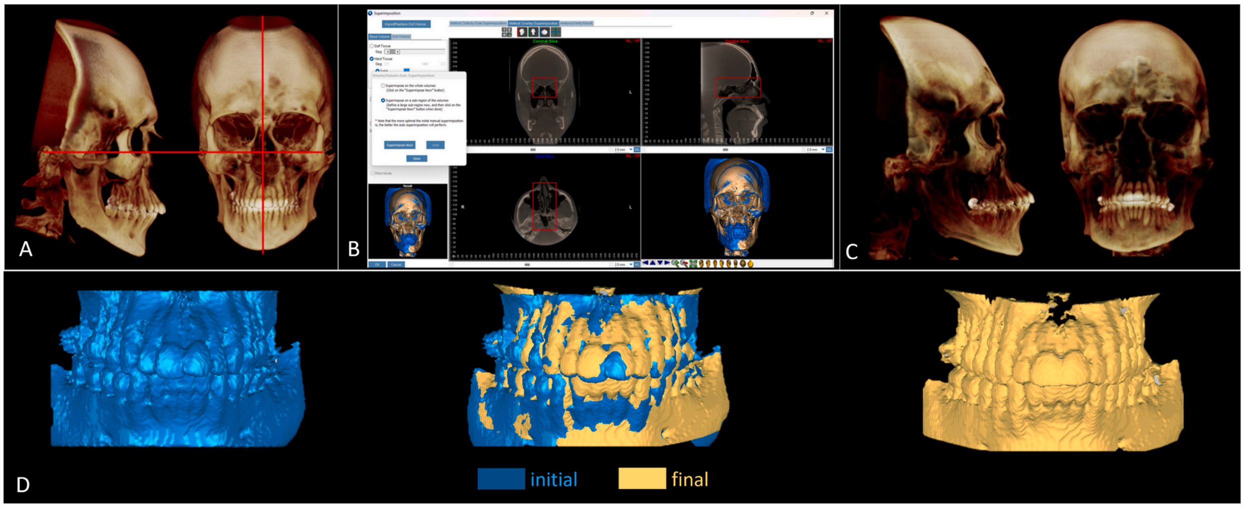

Fig 3. A, Initial CBCT (CBCT T0) orientation based on the Frankfort plane; **B,** Final CBCT (CBCT T1) scan (*yellow*) superimposed onto the initial CBCT (CBCT T0) (*blue*) using voxel-based image registration on the cranial base (region outlined in *red*); **C,** Final CBCT (CBCT T1) orientation after cranial base registration on the initial scan; **D,** Segmentation of the maxillary and mandibular jaws with adequate reproduction of the dental crowns of CBCT T0 and CBCT T1, which were exported as STL files.

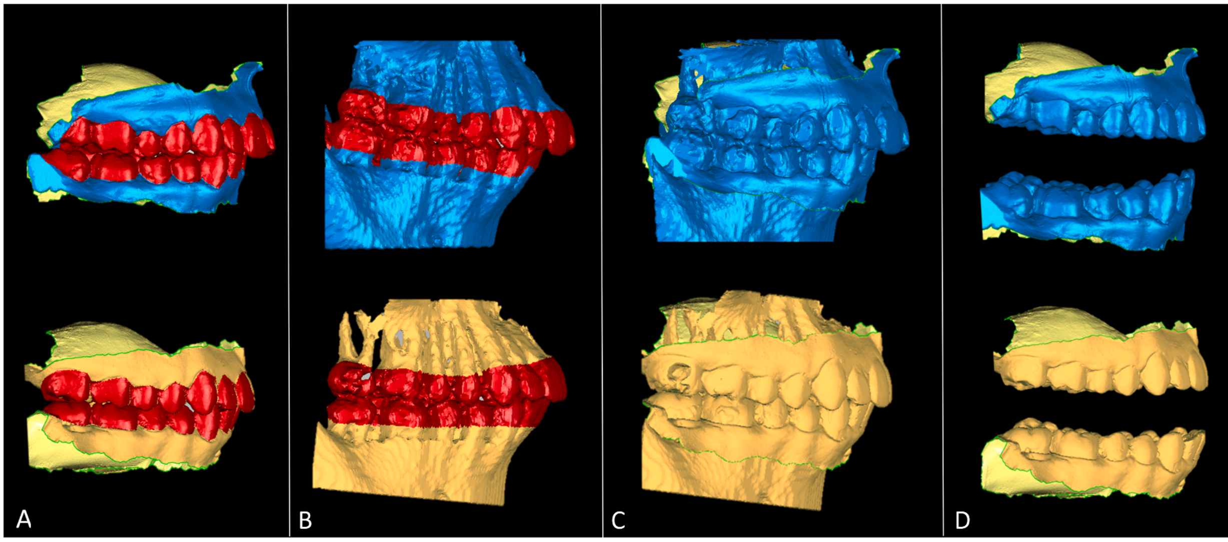

Fig 4. Workflow for registering digital models in occlusion to CBCT-derived models. Dental crown surfaces were selected on the digital models in occlusion (**A**) and on the CBCT-derived models (**B**) at T0 (*blue*) and T1 (*yellow*); **C,** Best-fit alignment was performed to register the digital models in occlusion to the corresponding CBCT-derived models; **D,** Individual maxillary and mandibular digital models were then superimposed onto the previously registered models in occlusion at T0 and T1. Pretreatment records are illustrated in *blue* and posttreatment records in *yellow*.

available for registration, the buccal and lingual surfaces of dental crowns of ModelsOcT0 and TomoOcT1 (Fig 4, *A*) with CBCT T0 and CBCT T1 were selected (Fig 4, *B*). Subsequently, single maxillary (UModelT0 and UTomoT1) and mandibular (LModelT0 and LTomoT1) digital models were individually superimposed on T0 and T1 digital models in occlusion (ModelsOcT0 and TomoOcT1) (Fig 4, *D*). These occlusion models had been previously registered to CBCT T0 and CBCT T1 (Fig 4, *C*), allowing landmark identification on the occlusal surfaces of the CBCT-based reference models, which provided the reference measurements used to assess the accuracy of the proposed method in Step 4. As the CBCT orientation was the reference for superimposition, this group was called tomography (t).

A narrow area below the two-thirds of the third palatal rugae and along the midpalatal suture was selected to superimpose T1 (UModelT1) and T0 (UModelT0) maxillary digital models using the best-fit alignment.[6,18,19] Then, the T1 digital model in occlusion (ModelsOcT1) was superimposed onto UModelT1. Finally, the T1 mandibular digital model (LModelT1) was superimposed using the occlusion as a reference (ModelsOcT1), resulting in the transfer of the mandibular position through the interarch occlusal relationship. Therefore, the mandibular arch positioning in the models' group should be interpreted as an occlusion-based transfer workflow rather than as an independent mandibular surface registration. As the superimposition reference areas were all anatomic structures of the digital models, this group was called models (m) (Fig 5).

Landmarks were defined at the central fossa of the first molars, at the cusp tip of the canines, and at the middle of the incisal edge of the central incisors. These landmarks were located on 6 models: UModelT0, LModelT0, UTomoT1, LTomoT1, UModelT1, and LModelT1 (Fig 6).

To establish an adequate reference system, a Cartesian coordinate system was defined individually for each patient based on the orientation of the pretreatment CBCT (CBCT T0). The axial plane, corresponding to the x- and y- axes, was determined using the labial commissure as a reference. The sagittal plane, corresponding to the y- and z- axes, was defined based on the midsagittal plane. The coronal plane, corresponding to the x- and z- axes, was established using the distal surfaces of the mandibular second molars as a reference.

To evaluate method accuracy, landmark displacements at T1 were assessed relative to the same pretreatment digital model (UModelT0 and LModelT0). For each superimposition strategy, the posttreatment models (UTomoT1 and LTomoT1 for the CBCT-based group, and UModelT1 and LModelT1 for the anatomic

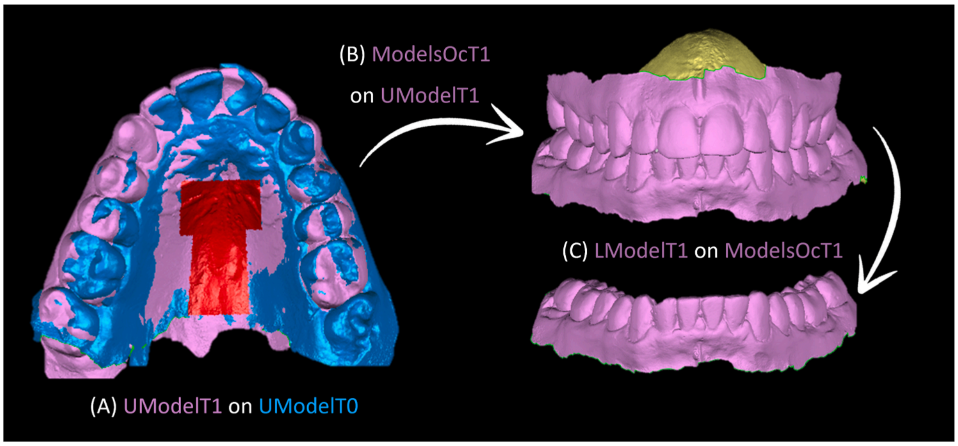

Fig 5. **A,** Superimposition of the final upper digital model on the initial upper (UModelT1 on UModelT0); **B,** Then, the T1 digital model in occlusion (ModelsOcT1) was superimposed to UModelT1; **C,** Finally, the T1 lower digital model (LModelT1) was superimposed using the occlusion as reference (ModelsOcT1). This represents the superimposition of the models group.

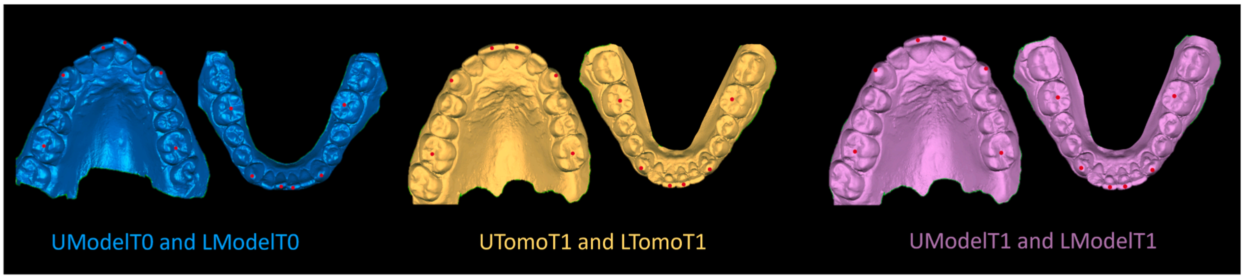

Fig 6. Marking of reference points on the central incisors, canines, and first molars of the initial digital models (*blue*); final digital models were superimposed using CBCT reference (*yellow*); final digital models were superimposed using the palatal rugae and occlusion references (*purple*).

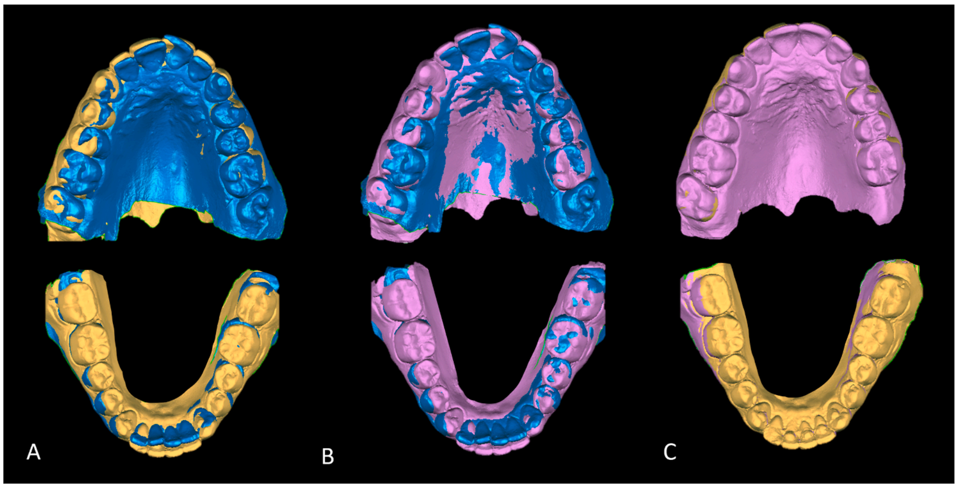

Fig 7. Comparison of superimposition methods using a common initial reference: **A,** Final models (UTomoT1 and LTomoT1) registered by CBCT-based superimposition; **B,** Final models (UModelT1 and LModelT1) registered using the palatal rugae and the occlusion; **C,** Differences between methods relative to T0.

Table I. Mean and standard deviation for tooth displacement for each axis (x, y, and z), for the tomography (t) and model (m) superimposition method and for each evaluator (1 and 2)

	Mean	*±standard deviation*
xt1	0.07	±0.75
xt2	0.13	±0.76
Δxt	−0.05	±0.09
xm1	−0.02	±0.70
xm2	−0.09	±0.77
Δxm	0.06	±0.09
yt1	0.38	±1.44
yt2	0.33	±1.46
Δyt	0.04	±0.18
ym1	0.19	±1.46
ym2	0.16	±1.44
Δym	0.02	±0.18
zt1	−0.83	±1.45
zt2	−0.76	±1.31
Δzt	−0.07	±0.17
zm1	−0.30	±1.24
zm2	−0.34	±1.31
Δzm	0.04	±0.16

Note. Differences (Δ) between evaluators were also analyzed.

reference-based group) were individually registered to T0 (steps 2 and 3, respectively), and landmark coordinates were obtained. Accuracy was then determined by comparing the differences in landmark displacements between the 2 T1 model sets relative to the common T0 reference (Fig 7).

For each landmark, x-, y-, and z- axis positions were recorded. Deviations in the z-axis represent vertical movements (extrusion or intrusion); in the y-axis, anteroposterior movements for the incisors (retrusion or protrusion) and lateral movements for the molars (mesialization or distalization); and those in the x-axis, lateral movements for the incisors (mesiodistal movements) or buccolingual movements for the molars. To determine the greatest divergences between the methods, mean differences for each landmark on each axis were compared.

Statistical analysis

As this was a retrospective methodological study aimed at assessing the accuracy and agreement between the 2 superimposition methods, an a priori sample size calculation was performed based on the detection of a clinically relevant difference between the methods. Using G*Power software (version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany), the analysis was based on a paired comparison between the CBCT-based reference workflow, which involved the integration of STL files into CBCT images, and the proposed digital model-based superimposition. A mean difference of 1.0 mm between methods was adopted a priori as a conservative methodological assumption for the sample size calculation. This value was selected based on previous digital model superimposition studies[3,6] reporting mean discrepancies below 1.0 mm and on the broader orthodontic convention that differences greater than 2.0 mm or 2 degrees in cephalometric assessment are generally considered clinically relevant. However, because no universally accepted clinical irrelevance threshold has been established for 3D digital model superimposition, the 1.0 mm value should be interpreted as an assumption rather than as a validated cutoff.

The significance level was set at $\alpha = 0.05$, with a statistical power of 80% ($\beta = 0.20$). Under these assumptions, the minimum required sample size was estimated to be 10 patients; this was therefore considered adequate for detecting clinically meaningful differences between the 2 superimposition approaches.

To evaluate the agreement between the proposed digital model superimposition method and the STL files integrated into CBCT data, intraclass correlation coefficients (ICCs) were calculated for the methods used by each evaluator. Two independent evaluators analyzed data from 10 patients, and ICC values were interpreted according to each method (t and m) for each axis (x, y, and z). Bland-Altman plots were created using ICCs to analyze the differences between the T1 methods (t and m) for both maxillary and mandibular teeth across all spatial coordinates. *P* values less than 0.05 were considered statistically significant. All statistical analyses were performed using IBM SPSS Statistics software (version 20.0; IBM Corp, Armonk, NY).

Table II. ICC and *P* values assessing interobserver reliability between evaluators (1 vs 2) for each method (t and m) and for each axis (x, y, and z)

Comparison	*ICC*	*P value*
xt1 vs xt2	0.93	0.68
xm1 vs xm2	0.87	0.71
yt1 vs yt2	0.98	0.61
ym1 vs ym2	0.97	0.98
zt1 vs zt2	0.96	0.26
zm1 vs zm2	0.98	0.36

RESULTS

The mean and standard deviation of the tooth displacement measurements along each axis (x, y, and z) between T0 and T1, for each method (t and m) and each evaluator (1 and 2) are shown in Table I. The mean values for each method were similar for all types of movement in both arches. The interevaluator

Table III. ICCs assessing intraobserver reliability and agreement between methods (t vs m) for each evaluator (1 and 2)

	ICC	
Comparison	*1*	*2*
xt vs xm	0.94	0.93
yt vs ym	0.98	0.97
zt vs zm	0.88	0.92

Table IV. Reproducibility of the methods for each evaluator (1 and 2)

	ICC	
Comparison	*1*	*2*
xt vs xt	0.81	0.95
xm vs xm	0.91	0.96
yt vs yt	0.99	0.99
ym vs ym	0.97	0.99
zt vs zt	0.95	0.99
zm vs zm	0.99	0.99

differences (Δ) ranged from −0.07 to 0.06 mm, which were not considered clinically relevant.

Table II presents the ICCs used to assess interobserver reliability between evaluators 1 and 2 for each method and for each axis (x, y, and z). The ICC values were high, ranging from 0.87 to 0.98. Student *t* test revealed no statistically significant differences between the evaluators for any axis in either method ($P > 0.05$), indicating excellent interobserver reliability.

Intraobserver reliability and agreement between methods are shown in Table III. High ICC values (≥0.90) were observed for all measurements except for the z-axis (vertical displacement), in which the ICC for evaluator 1 was 0.88. These findings demonstrate a high level of agreement between the 2 superimposition methods for both evaluators.

The reproducibility of the methods assessed by ICCs is shown in Table IV. Both evaluators demonstrated high reproducibility, with ICCs ranging from 0.81 to 0.99 for evaluator 1 and 0.95 to 0.99 for evaluator 2.

Figure 8 shows the Bland-Altman plots, in which the y-axis represents the differences between the methods (Δ), and the x-axis represents their mean. Bland-Altman analysis demonstrated good agreement between the T1 methods (tomography and models) for both maxillary and mandibular teeth across all spatial coordinates. For the x-coordinates, which describe lateral movements for the incisors (mesiodistal movements) or buccolingual movements for the molars, the 95% limits of agreement ranged from −0.63 to 0.95 for the maxillary arch and from −0.57 to 0.91 for the mandibular arch (Fig 8, *A* and *D*). For the y-coordinates, which show anteroposterior movements for the incisors (retrusion or protrusion) and lateral movements for the molars (mesialization or distalization), the limits of agreement ranged from −0.75 to 1.10 for maxillary teeth and from −0.65 to 1.02 for mandibular teeth. For the z-coordinates, wider limits of agreement were observed, ranging from −2.07 to 1.13 for maxillary teeth and from −2.00 to 1.05 for mandibular teeth, indicating greater variability in the vertical dimension compared with the transverse and anteroposterior directions.

DISCUSSION

The present study proposes and validates a digital model superimposition technique for orthodontic patients that can be applied without CBCT imaging and, therefore, without additional radiation exposure. The novelty of the present study lies in validating a complete radiation-free workflow for tooth-movement assessment in adult nonextraction patients, in whom maxillary registration is performed on the palatal rugae and mandibular arch positioning is transferred through the interarch occlusal relationship.

Previous research has consistently demonstrated the reliability of the palatal rugae for evaluating tooth movement in the maxillary arch before and after orthodontic treatment.[1-3,11,14,16,18,22,24,25] In particular, the second and third palatal rugae are considered stable reference structures, whereas the first ruga is more susceptible to displacement,[26] especially during incisor retraction, with or without extractions.[1,2,14] Several studies have identified the medial rugae points and the area approximately 5 mm posterior to the third palatal rugae as highly stable and reliable landmarks, often regarded as the reference standard for maxillary model superimposition.[1,2,14] Accordingly, in the present study, maxillary arch superimpositions were based on these regions to maximize stability and consistency.

In contrast, mandibular model superimposition remains less studied, largely because of the scarcity of stable anatomic landmarks in the mandibular arch.[27] No consensus has yet been reached regarding the optimal technique for serial 3D mandibular superimpositions, and conventional registration references each present inherent limitations. For this reason, the present study used the interarch occlusal relationship as a transfer step for mandibular-arch positioning, with the results compared with CBCT-based measurements. It is important to acknowledge that occlusal changes occurring during orthodontic treatment may influence the stability of this reference, particularly affecting the vertical

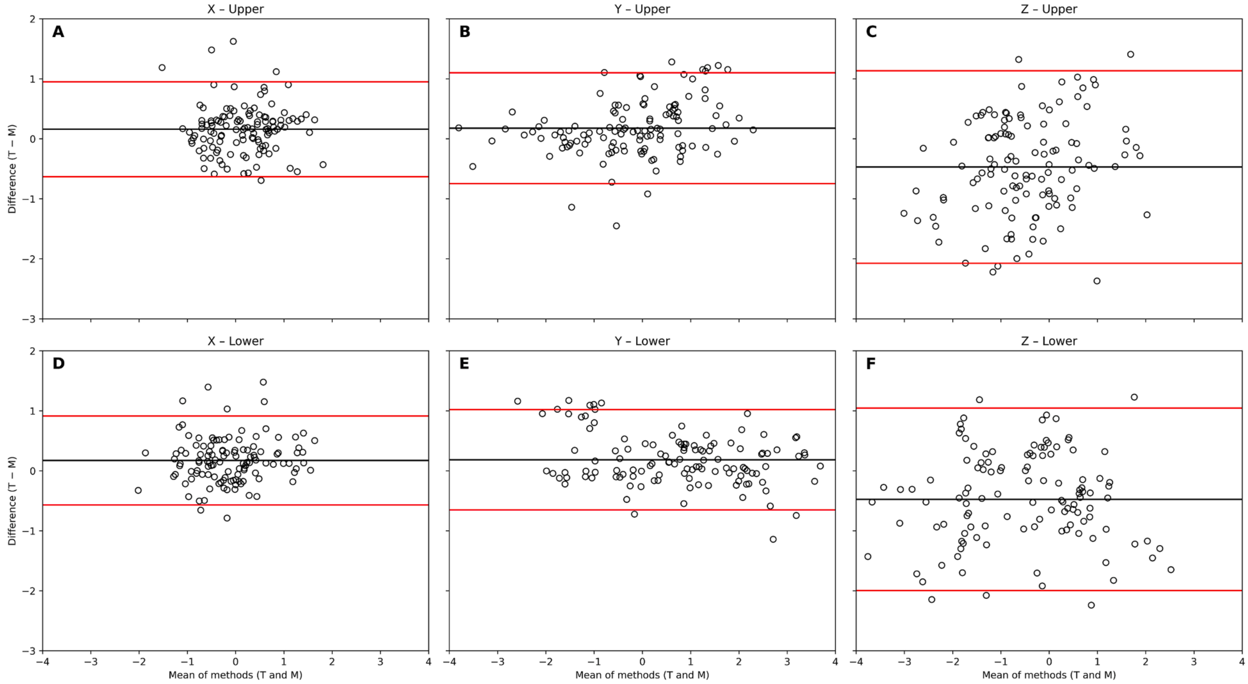

Fig 8. Bland-Altman plots showing agreement between superimposition methods for the maxillary arch (**A-C**) and for the mandibular arch (**D-F**). The y-axis represents the difference between methods (Δ), and the x-axis represents the mean of the methods.

dimension. Additionally, because mandibular-arch positioning depends on sequential maxillary registration followed by transfer through the T1 occlusal relationship, cumulative error across steps cannot be excluded.

Although the occlusal plane is sensitive to changes in its orientation, potentially introducing variability in z-axis measurements, as shown in the Bland-Altman plots (Fig 8, *C* and *F*), it demonstrated greater consistency in this study than previously proposed anatomic references.[3,21] However, despite this inherent sensitivity, the interarch occlusal relationship-based superimposition demonstrated clinically acceptable agreement with the STL-CBCT integration in the present study. These findings are in accordance with those of Bailey,[28] in which the second and third palatal rugae were considered stable in the sagittal and transversal planes, with less precision in the vertical plane.

The difficulty in defining reliable mandibular references is supported by previous findings: An et al[3] reported that alveolar surfaces were unreliable in patients without mandibular tori because of extensive remodeling during orthodontic treatment, particularly in growing individuals, whereas Souza et al[21] noted reduced reliability when restorative or periodontal procedures occurred during treatment. Alternative approaches have been proposed, such as using bilateral mandibular tori[3] or surface-based methods,[6] both of which have shown mean discrepancies of less than 1 mm. Similarly, Oueiss et al[13] found no statistically significant differences between 2D cephalometric and 3D model superimposition measurements.

Patient selection was a deliberate methodological choice. Most of the previous research on 3D model superimposition has focused on adult patients, as growth-related changes complicate longitudinal comparisons.[14,25] In the present study, only nongrowing patients were included to validate the method without the confounding influence of growth, in line with evidence on anatomic stability[29] and with ethical considerations to minimize radiation exposure in younger patients. The sample size in the literature varies widely, with substantial methodological heterogeneity and limited standardization.[3,6,12,13,21] Studies have ranged from single-case reports to larger cohorts. In the present study, 10 patients were included, consistent with prior validation research demonstrating that this sample size is sufficient for drawing reliable conclusions.

Traditionally, orthodontic tooth movement has been assessed by superimposing pre- and posttreatment cephalometric radiographs on stable skeletal landmarks.[3,14-16,30] However, this 2D method is limited by magnification errors, image distortion, and superimposition of bilateral structures, all of which complicate landmark identification and introduce tracing errors.[3,14,17] Moreover, cephalometric radiographs lack the comprehensive, high-resolution detail of CBCT or 3D intraoral models. Notably, Liu et al[31] demonstrated that lateral cephalogram superimpositions and palatal rugae-based 3D model superimpositions are equally reliable, supporting the use of radiation-free digital methods when appropriate. For these reasons, the integration of scanned dental models into CBCT images was adopted as the reference for comparison in the present study.

Clinically, discrepancies greater than 2 mm or 2 degrees on lateral cephalograms are generally considered significant. In this context, discrepancies of less than 1 mm between the present method and CBCT-based superimposition can be considered more than acceptable for assessing tooth movement, particularly given that the method is radiation-free. The 3D model superimposition approach evaluated here, using palatal rugae for the maxillary arch and the interarch occlusal relationship for the mandibular arch, demonstrated excellent intraobserver reliability (Table III) and reproducibility (Table IV). It offers an accurate, efficient, and noninvasive option for assessing orthodontic treatment outcomes in adult nonextraction cases.

In the present study, the superimpositions to assess tooth movement were performed on digital models obtained by scanning plaster casts with an intraoral scanner rather than on direct intraoral scans. This additional digitization step may introduce minor artifacts, which, as demonstrated by Henninger et al[32] can lead to distortions in superimposition outcomes. In addition, although the measurements were performed using high-reliability software,[33,34] they relied on manually placed landmarks positioned by 2 operators on the maxillary and mandibular molars, canines, and incisors at both the pre- and posttreatment stages. This procedure may increase the potential for intra- and interexaminer variability. A possible refinement would be to apply centroid calculations after highlighting a surface with precise coordinates, a method previously used successfully by Heni et al,[35] thereby minimizing distortions attributable to measurement errors.

Additionally, the CBCT-based reference workflow used in this study included visually adjusted thresholding for crown segmentation and surface-based registration using selected dental crown surfaces, which may introduce some operator dependence. This approach was selected because, at the time the study was conducted, it represented an established and feasible workflow within the available software, allowing for improved crown representation for landmark localization. However, more recent deep learning-based segmentation and registration tools may reduce operator dependence and improve workflow robustness.

Future research should investigate the method's applicability in growing patients and in more complex treatment scenarios, such as extractions or orthognathic surgery. Establishing universally accepted, reliable anatomic landmarks, particularly for the mandibular arch, will be key to integrating 3D model superimposition into routine orthodontic practice as a practical, accurate, and radiation-free alternative to CBCT.

CONCLUSIONS

3D digital model superimposition, using the palatal rugae as a reference for the maxillary arch and the transfer of the mandibular position through the interarch occlusal relationship, is a reliable and reproducible method for assessing orthodontic tooth movement in nongrowing patients treated without extractions.

AUTHOR CREDIT STATEMENT

Beatriz Rosa contributed to the conception of the study, data acquisition, data analysis and interpretation, and prepared the initial draft of the manuscript. Carlo Bosoni participated in data analysis and interpretation. David Silveira Alencar and Felipe de Assis Ribeiro Carvalho were responsible for structuring the methodology. Lorenzo Franchi and Jose Augusto Miguel critically revised the manuscript for intellectual content and approved the final version for submission. Flavia Artese contributed to the study conception and design, data analysis and interpretation, drafting of the manuscript, and final approval of the version to be submitted.

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