kVp, mA, and voxel size effect on 3D voxel-based superimposition

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ABSTRACT

Objectives: To evaluate the effect of changing kVp, mA, and voxel size on the accuracy of voxel-based superimposition on the anterior cranial base.

Materials and Methods: Cone beam computed tomography (CBCT) scans were taken on a phantom skull using different kVp, mA, and voxel size combinations. CBCT scans were superimposed using commercially available software. Two separate open-source software programs were used to generate a three-dimensional (3D) color map objective assessment of the differences in seven different regions: Nasion, Point A, Zygomatic (right and left), Point B, and Gonial (right and left). Each region had around 200 points that were used to calculate the mean differences between the superimpositions.

Results: Intraclass correlation showed excellent reliability (0.95). Lowering the kVp made the biggest difference, showing an average discrepancy of 0.7 ± 0.3 mm, and a high mean of 1.4 ± 0.3 in the Right Gonial region. Lowering the mA showed less of a discrepancy, with an average of 0.373 ± 0.2 mm, and the highest discrepancy, also on the Right Gonial Area, of 0.7 ± 0.1 mm. The voxel size had the least impact on the accuracy of registered volumes, with mean discrepancy values of less than 0.2 mm.

Conclusions: Using different CBCT settings can affect the accuracy of the voxel-based superimposition method. This is particularly the case when using low kVp values, while changes in mA or voxel sizes did not significantly interfere with the superimposition outcome. (*Angle Orthod.* 2020;90:269–277.)

KEY WORDS: CBCT; Voxel-based superimposition

INTRODUCTION

Cone beam computed tomography (CBCT) is a useful tool to diagnose the dentomaxillofacial complex and provide a balance between performance and value with a lower radiation exposure compared with traditional spiral computerized tomography (CT).[1] CBCT brought many advantages to the clinical field, including significant improvement on location of impacted teeth, diagnosis of oral abnormalities, accurate measurement of the upper airway, detailed assessment of alveolar bone heights, among others.[2] A 3D superimposition of two CBCTs also provided a more thorough analysis, and access to the transverse dimension.

Three different ways can be used to superimpose two CBCT volumes: landmark-based superimposition, surface-based superimposition, and the voxel-based method. The landmark method was the first one used for CBCTs superimposition. Locating landmarks in cephalograms is not precise because of possible differences in head orientation, differential magnification, lack of the depth, etc.[3] Identification of landmarks on a CBCT has been shown to be more precise than in a cephalogram.[4–6] Though smaller, each landmark still had an envelope of error, and if a plane with three or four landmarks is used as the basis for a superimposition, the precise location of each landmark is essential. Another option is surface-based superimposition, which comprises more information than a single point representing the anatomical structure. Ong et al.

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found that the surface-based superimposition method can be used to analyze 3D effects of rapid maxillary expansion (RME).[7] Gkantidis et al. found that landmark-based superimposition technique was less accurate than the surface-based superimposition method.[8] Koerich et al. found that, for CBCT scans with small field of view (FOV), 3D regional superimposition was a valid, fast, and reliable way to superimpose both the maxilla and mandible.[9]

Cevidanes et al. presented the voxel-based method that matched the grayscale of the voxels in the area of reference to superimpose CBCT volumes. This method used two open-source programs ITK-SNAP (http://www.itksnap.org) and 3D Slicer (http://www.slicer.org). The voxel-based method has been used to compare changes in orthognathic surgery patients, evaluate soft tissues changes, and study growing patients.[10,11] Almukhtar et al. compared the accuracy of surface- and voxel-based registration using Maxilim software (Medicim-Medical Image Computing, Belgium). They found no statistically significant differences between the two methods when analyzing skeletal; however, the voxel-based method was more accurate when dealing with soft tissue.[12] One of the reported shortcomings of the Cevidanes' method was that it was time-consuming, making it impractical in clinical situations. Koerich et al. studied mandibular dentoalveolar changes in growing patients using a rapid 3D voxel-based mandibular superimposition method that took around 5 minutes. The internal part of the symphysis extending to the first molar was used as the reference. They concluded that this method was accurate to assess the dentoalveolar changes near the registration area but not for the condyles and ramus area.[13] Choi and Mah introduced a new method to superimpose CBCT scans using OnDemand3D,[14] which was validated by Weissheimer et al.[15] Another fast and practical approach to voxel-based superimposition was introduced by Dolphin 3D software (Patterson Dental, St. Paul, MN). Bazina et al. concluded that Dolphin 3D voxel-based superimposition was precise and reliable.[16] It is common knowledge that using higher radiographic settings, such as milliamperage (mA) and kilovolt peak (kVp), results in higher quality volumes, but it is not known how or if the image quality would have any effect on the voxel-based superimposition outcome.

The purpose of this study was to evaluate the effect of changing kVp, mA, and voxel size on the accuracy of voxel-based superimposition on the anterior cranial base.

MATERIALS AND METHODS

This was a prospective study using CBCT scans taken on a phantom skull (The Phantom Laboratory, Salem, NY). The phantom consisted of a human skull inside a material that was radiographically equivalent to soft tissue (Figure 1). All scans were taken using the Carestream CS9300 scanner (Carestream Health, Inc., Rochester, NY). The Carestream CS9300 can take CBCT volumes with different FOVs ranging from 5 × 5 cm^2 to 17 × 13.5 cm^2 with operator-controlled choice of different parameters such as kVp, mA, and voxel size.

Figure 1. The phantom skull.

For this study, the largest FOV (17 × 13.5 cm^2) was used, since it is the only size that shows the anterior cranial base that is needed for the superimposition method tested. For the large FOV, the scanning time is always 11.30 seconds, while the operator has different options regarding mA, kVp, and voxel size. KVp ranges between 60 and 90, mA between 2 and 15, and two options for voxel size, 300 and 500 μm. To limit radiation exposure, the scanner does not allow the use of both high kVp and high mA. For example, the highest mA that can be used with (81–85) kVp is 12 and the maximum mA that can be used with (86–90) kVp is 10. Different combinations of kVp, mA, and voxel size were used to examine the effect on voxel-based superimposition. To evaluate the effect of each of the three variables, two variables were fixed while the third was altered. Table 1 shows all combinations tested, and their equivalent radiation emission doses.

Since the subject was the same (phantom), in theory, if there was no effect on the superimposition, a perfect fit would be expected with no differences. Each group to be compared was divided into a Settings 1 (S1) and Settings 2 (S2). For each pair of CBCT volumes (S1 and S2), S2 was registered on S1 anterior cranial base using Dolphin 3D software. The superimposition method included an initial approximation of both volumes using three landmarks. The landmarks used were the left and right frontozygomatic structures and the left mental foramen. The area to be matched during the superimposition was then selected. The area of the anterior cranial based was defined by a box including: (1) sella turcica, (2) planum sphenoidale, (3) cribriform plate, and (4) the inner cortex on the frontal

Table 1. CBCT Settings. All CBCTs Have the Same FOV: 17 × 13.5 cm and Equal Time Exposure: 11.3 Seconds[a]

	CBCT Settings (kVp/mA/voxel size)	Radiation Emission Dose (mGy.cm²)
Reliability test	90kVp 4mA 300µm	1585
kVp effect	60kVp 10mA 300µm	1110
	70kVp 10mA 300µm	1915
	80kVp 10mA 300µm	2866
	90kVp 10mA 300µm	3963
mA effect	90kVp 2mA 300µm	793
	90kVp 4mA 300µm	1585
	90kVp 8mA 300µm	3171
	90kVp 10mA 300µm	3963
Voxel size effect	90kVp 2mA 300µm	793
	90kVp 2mA 500µm	793
	90kVp 4mA 300µm	1585
	90kVp 4mA 500µm	1585
	90kVp 10mA 300µm	3963
	90kVp 10mA 500µm	3963

[a] CBCT indicates cone beam computed tomography; FOV, field of view; kVp, kilovolt peak; mA, milliamperage.

sinus (Figure 2). After the superimposition was completed, the registered S2 (Reg S2) volume was exported in a DICOM (Digital Imaging and Communications in Medicine) format.

Creating 3D Color-Coded Maps Using Open-Source Programs (ITK-snap and 3D Slicer)

The next step was to open S1 and Reg S2 DICOM files separately using ITK-snap and convert them to GIPL (Guys Imaging Processing Lab) format for easy computing. The Intensity segmenter tool from 3D Slicer software was then used to segment the whole skull, then three tools in 3D Slicer were used: a Model Maker tool to create a surface model, Model-to-Model

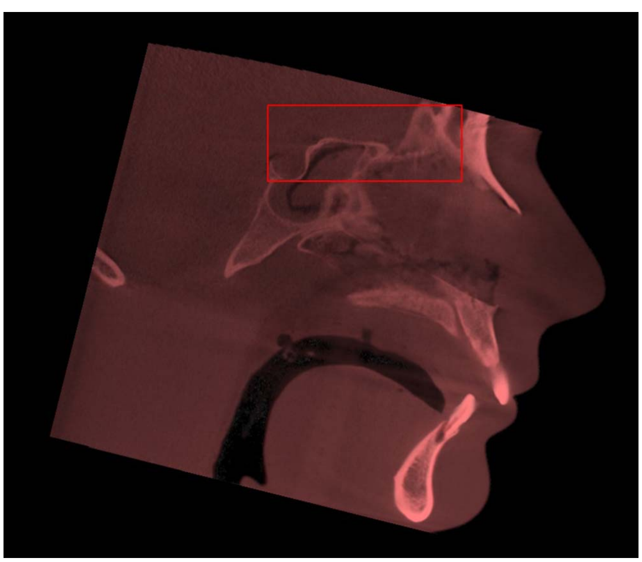


Figure 2. The area used to superimpose S1 and Register S2.

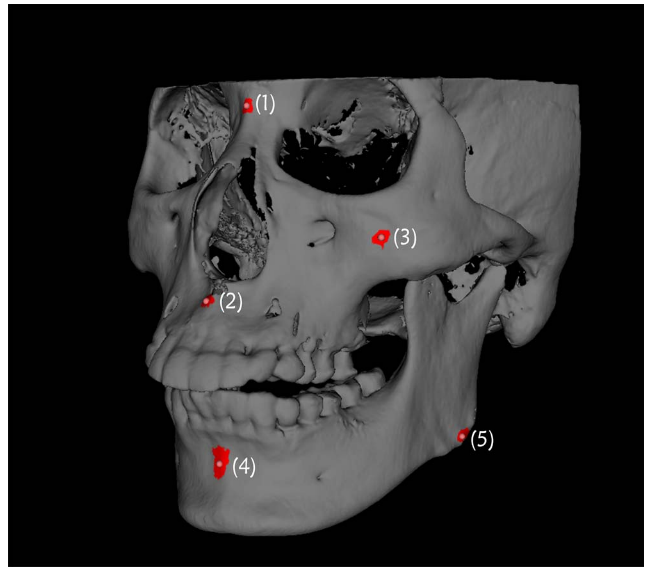


Figure 3. Regions used to measure mean distance between S1 and Registered S2: (1) nasion, (2) point A, (3) Zygomatic (right and left), (4) point B, and (5) gonial (right and left).

distance tool to measure the absolute-closest-point between the two surface models and Shape-Population-Viewer tool to visualize the differences using color-coded maps. To make it easier to compare the effect of each variable, the same scale was used to interpret all color-coded maps. Pick and paint and mesh statistics tools were also used to calculate the differences between the two scans in seven different regions (Figure 3). Each area had around 200 points on the surface that were used to calculate the mean difference between the two superimposed 3D model surfaces. The lowest and highest settings could not be compared because ITK-snap and 3D slicer were not able to generate 3D models for the lowest settings due to the high level of noise.

RESULTS

To evaluate the methodology, a test was performed by taking two 3D volumes using the manufacturer-suggested settings for an average adult patient (90 kVp, 4 mA) with 300 µm voxel size in two different orientations and superimpose them on the cranial base. The color-coded map showed no difference between S1 and Reg S2 when using the same settings (Figure 4). The means and standard deviations in the seven regions are shown in Table 2.

kVp Effect

Three CBCTs with 10 mA, 300 µm voxel size and with different kVp settings (60, 70, 80) were superimposed on the cranial base of S1 (90 kVp, 10 mA, 300 µm). Color-coded maps displayed differences up to

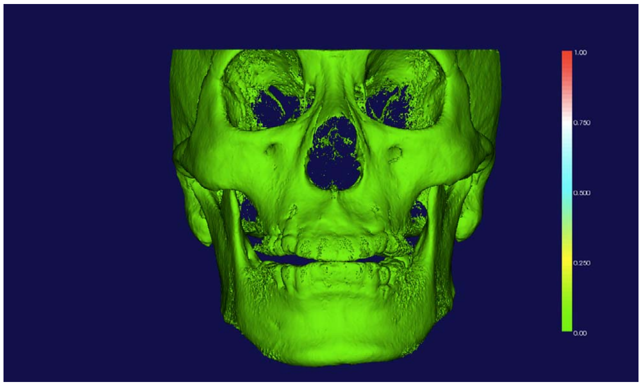


Figure 4. Color-coded map shows no difference when two CBCTs with the same settings and different orientation were registered. CBCT indicates cone beam computed tomography.

(1.43 ± 0.309 mm) in the right gonial region when 60 kVp scan was compared to 90 kVp scan (Figure 5, Table 3).

mA Effect

Three CBCTs with 90 kVp, 300 μm and altered mA settings (2, 4, 8) were registered on the cranial base of S1 (10 mA, 90 kVp, 300 μm). Color-coded maps showed some differences between the registered volumes. The biggest difference was up to 0.704 ± 0.143 mm in the right gonial region when 2mA was superimposed on 10mA. These differences can be seen in Figure 6 and Table 4.

Voxel Size Effect

Three combinations with different voxel size (300 and 500) μm were used to fulfill this purpose (90 kVp, 2 mA, 90 kVp, 4 mA, and 90 kVp, 10 mA). Figure 7 shows some differences between registered volumes with different voxel size settings. After comparing these differences to the numbers after changing kVp and mA settings, altering the voxel size had the least impact on the accuracy of the voxel size superimposition volumes (Table 5).

Table 2. Mean± SD in mm When Registered Two CBCTs With Same Settings And Different Orientation[a]

Region	Mean	SD
Nasion	0	0.001
A	0.002	0.003
Zygo RT	0	0
Zygo LT	0.003	0.005
B	0.003	0.004
Gonial RT	0.008	0.009
Gonial LT	0	0

[a] LT indicates left; RT, right; SD, standard deviation; Zygo LT, zygomatic left; Zygo RT, zygomatic right.

DISCUSSION

Several standards have been used to assess the quality of CBCT volumes: contrast-to-noise ratio (CNR) was considered the most commonly accepted method.[17] The grayscale, quality, and contrast-to-noise ratio of any CBCT image is determined by its settings, which includes FOV, kVp, mA, voxel size, and other factors.[17,18]

FOV selection has a direct effect on resolution and contrast of CBCT volumes. Zachary et al. found that smaller FOV volumes were superior to larger FOV in evaluating the temporomandibular joint erosive changes.[19] Hassan et al. noted similar results in detecting vertical root fractures with different sizes of FOV.[20] Other studies found a relationship between FOV and other settings but, because one size for FOV was used, the effect of changing FOV was out of the focus of this study.

Siegel et al. found similar results showing that changing the kVp affected the quality of the image.[21] Decreasing kVp resulted in poor quality volumes with more noise. When the kVp difference increased between two registered CBCT volumes, more error in superimposition was observed (Figure 5).

After comparing all color-coded maps in Figure 6, a direct relationship was found between noise, reducing mA, and the difference between registered CBCT volumes. A 1 mm alteration in superimposition was found when high, moderate, and lowest settings were superimposed to the highest mA settings for 90 kVp mainly in the area of the teeth. Because teeth are denser than bone, lowering mA settings had a greater impact on teeth compared to bone. A difference up to 0.704 ± 0.143 mm was noted in the right gonial region when the 2 mA image was superimposed on the 10 mA image. Nonetheless, image quality remained acceptable for a moderate or large mA setting reduction compared with the manufacturer recommended settings.[22] Some studies on CBCT volumes taken by CS 9300 found that adequate CBCT volume quality could be obtained by using low kVp and moderate to high mA, which reduced the amount of radiation exposure by about 30% compared with the manufacturer recommended settings.[23,24]

Two voxel sizes were registered (300 and 500) μm in three different settings. An inverse relationship was found between voxel size and image quality. A difference of up to 0.5 mm was found between CBCTs with low settings (Figure 7). This difference went to 0.25 between high setting registered CBCTs. Since the quality was better, the software was able to detect more shades of grayscale and matched more voxels. It seemed that Dolphin does not alter the voxel size when two voxel sizes are used. Some other software

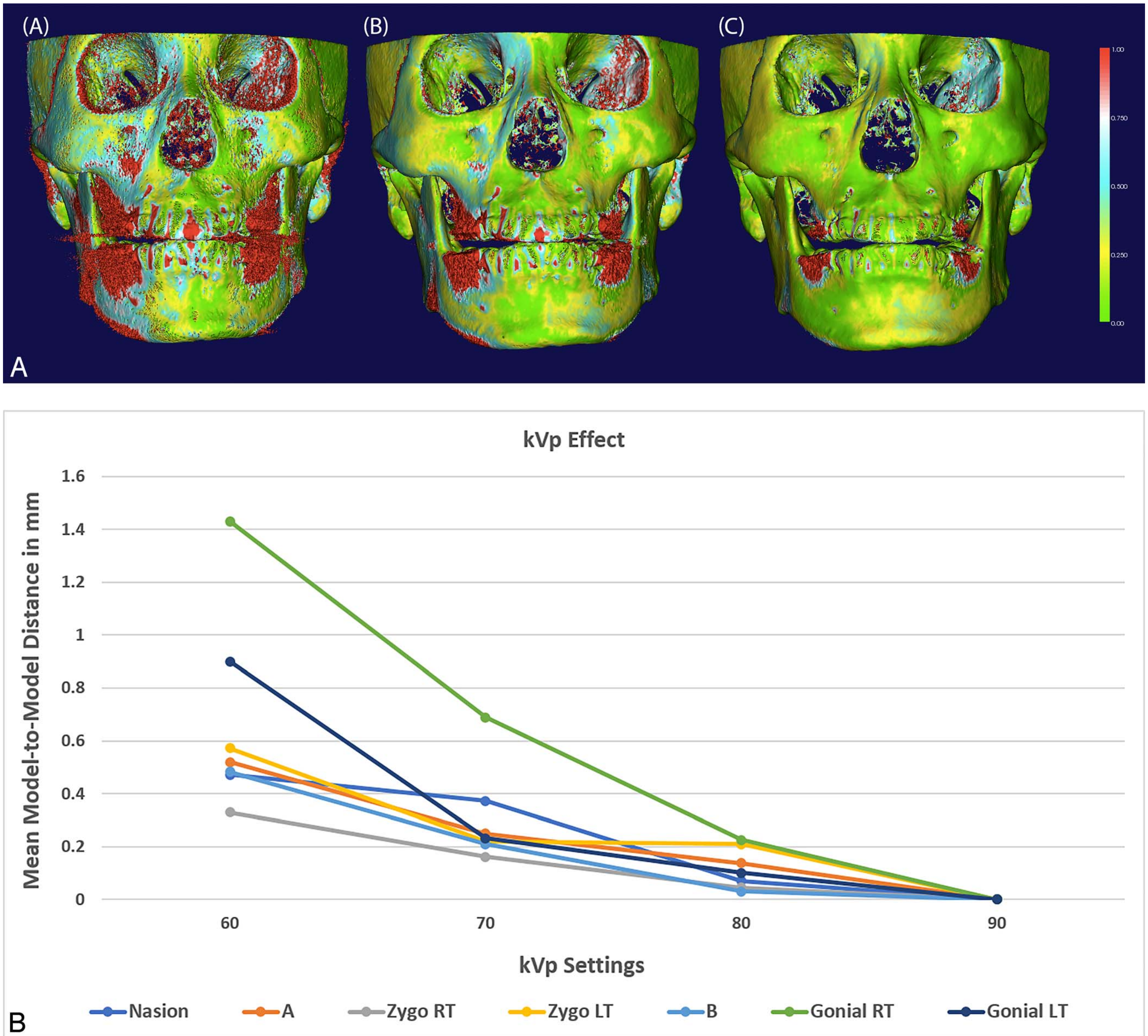
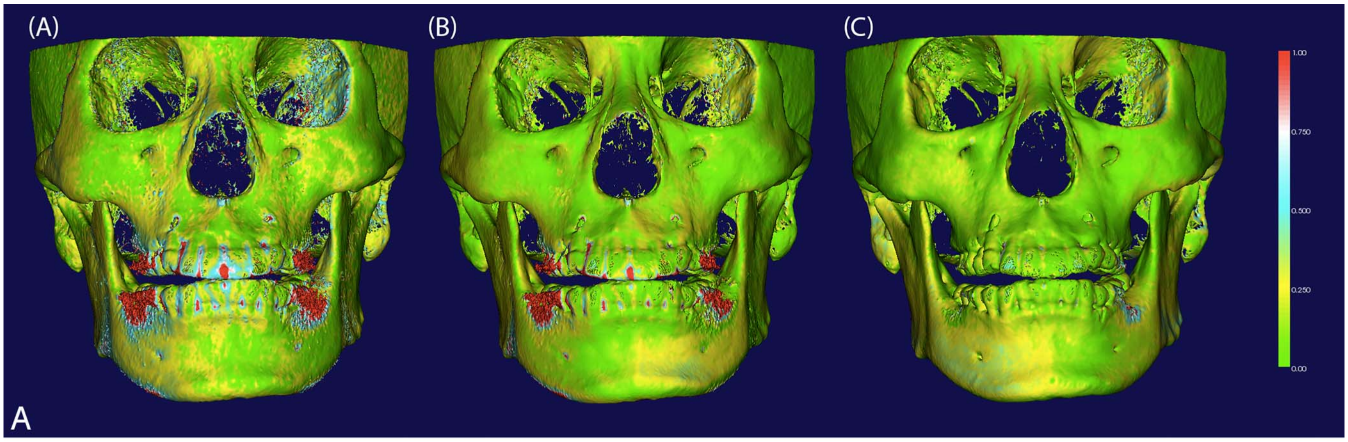


Figure 5. Different kVp settings with other settings fixed at 10 mA and 300 μm. (A) Color-coded maps showing superimposed CBCTs with different kVp settings: (A) 60 vs 90 kVp; (B) 70 vs 90 kVp; and (C) 80 vs 90 kVp. (B) Graphic showing different kVp settings compared to model-to-model distance. The closer the models, the more accurate is the superimposition. CBCT indicates cone beam computed tomography; kVp, kilovolt peak.

Table 3. kVp Effect. Mean Differences and Standard Deviations of Different Anatomical Regions After a Voxel-Based Superimposition of the Same Phantom Taken Using Different kVp Settings: (A) 60 vs 90 kVp; (B) 70 vs 90 kVp; and (C) 80 vs 90 kVp. All Images had Fixed 10 mA and Fixed Voxel Size at 300 μm[a]

	(A)				(B)				(C)			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Nasion	0.003	0.92	0.471	0.198	0.07	0.53	0.372	0.091	0.007	0.141	0.071	0.031
A	0.053	1.246	0.519	0.321	0.002	0.83	0.249	0.226	0.101	0.178	0.138	0.02
Zygo RT	0.191	0.627	0.329	0.096	0.028	0.25	0.161	0.058	0.001	0.1	0.045	0.024
Zygo LT	0.358	1.046	0.572	0.12	0.087	0.308	0.221	0.039	0.082	0.288	0.21	0.047
B	0.255	1.071	0.482	0.188	0.016	0.716	0.209	0.123	0.112	0.052	0.031	0.006
Gonial RT	0.484	2.029	1.43	0.309	0.519	0.966	0.689	0.104	0.002	0.399	0.225	0.099
Gonial LT	0.776	1.025	0.899	0.056	0.062	0.324	0.231	0.048	0	0.387	0.1	0.068

[a] kVp, kilovolt peak; LT indicates left; RT, right; SD, standard deviation; Zygo LT, zygomatic left; Zygo RT, zygomatic right.



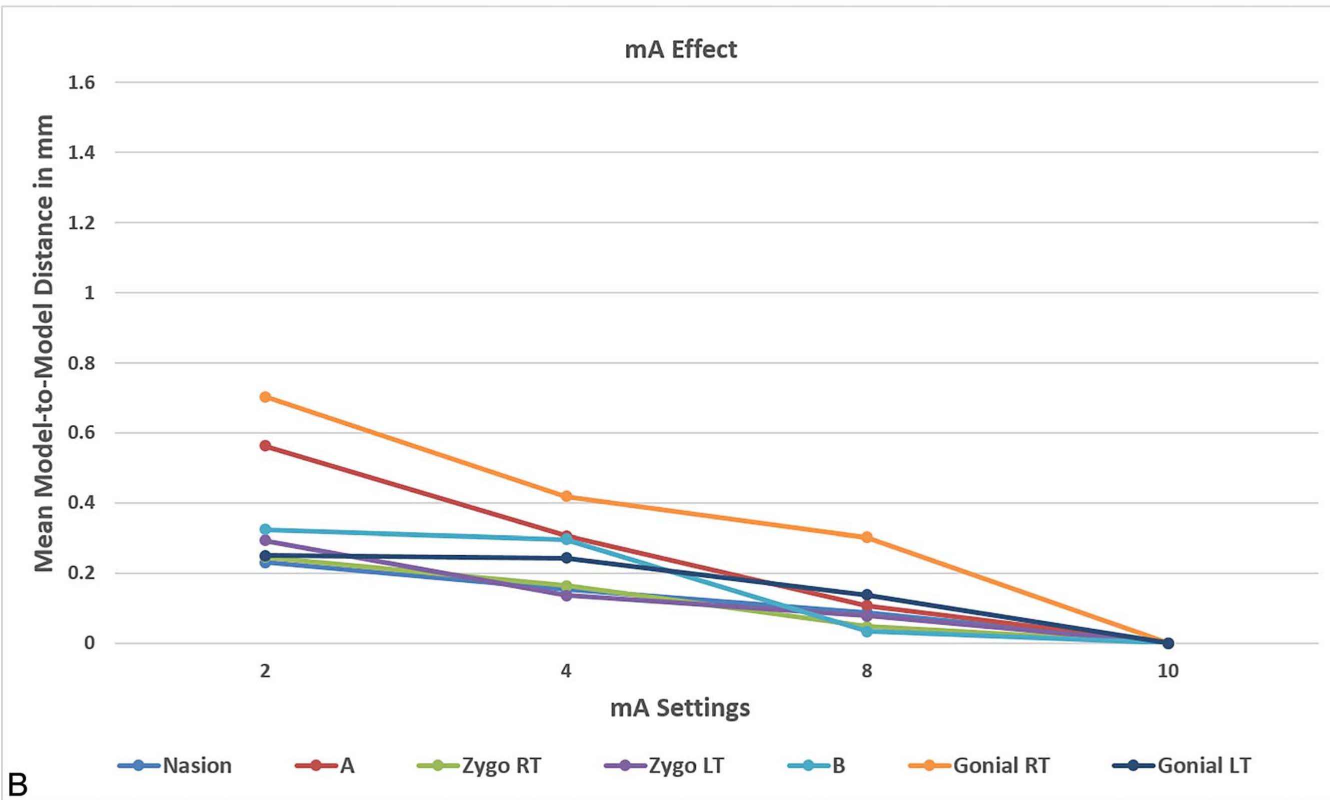


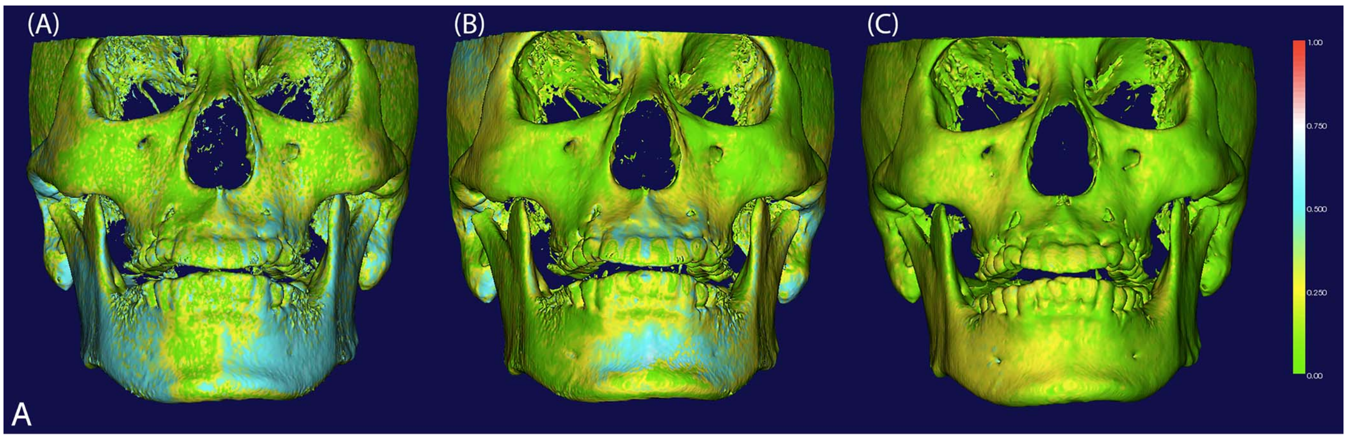
Figure 6. Different mA settings with other settings fixed at 90 kVp and 300 μm. (A) Color-coded maps illustrating the alteration in superimposed CBCTs when different mA parameters have been used. (A) 2 vs 10 mA; (B) 4 vs 10 mA; and (C) 8 vs 10 mA. (B) Graphic showing different mA settings compared to model-to-model distance. The closer the models, the more accurate is the superimposition. CBCT indicates cone beam computed tomography; mA, milliamperage.

programs can be used to resize voxel size of one of the CBCT volumes to match the other image before the registration step to minimize the registration errors. Maret et al. studied the effect of voxel size on the accuracy of 3D reconstructions and volumetric measurements in CBCT volumes. Part of that study compared three different voxel sizes (76, 200, and 300) μm. A relationship was found between voxel size and image quality; the bigger voxel size caused less sharpness in the CBCT image. No difference was found in measurements up to 200 μm despite a slight underestimation. This underestimation became significant starting from 300 μm and above.[25] Hassan et al. compared the quality of reconstructed 3D models from three different CBCT volumes settings. It was discovered that models reconstructed from CBCT images taken with large voxel size lacked the visibility of occlusal surfaces, interproximal space between teeth and alveolar bone.[26] Remarkably, using large voxel size reduced image noise due to averaging grayscales

Table 4. Mean Differences and Standard Deviations in mm Between Registered CBCTs when altering mA settings. (A) 2 vs 10 mA; (B) 4 vs 10 mA; and (C) 8 vs 10 mA. Both kVp and Voxel Size Remain Fixed at (90 kVp and 300 μm) Respectively[a]

	(A)				(B)				(C)			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Nasion	0.117	0.298	0.231	0.041	0.005	0.265	0.154	0.041	0	0.216	0.088	0.051
A	0.078	1.081	0.563	0.21	0.002	0.696	0.307	0.188	0.024	0.144	0.108	0.024
Zygo RT	0.005	0.471	0.246	0.079	0.081	0.245	0.164	0.042	0	0.112	0.048	0.028
Zygo LT	0.116	0.697	0.294	0.143	0.019	0.26	0.137	0.056	0.026	0.125	0.078	0.02
B	0.181	0.405	0.324	0.049	0.019	0.98	0.297	0.181	0.001	0.09	0.034	0.02
Gonial RT	0.317	1.129	0.704	0.143	0.195	0.644	0.419	0.104	0.214	0.376	0.302	0.031
Gonial LT	0.009	0.401	0.251	0.097	0.067	0.434	0.244	0.102	0.001	0.224	0.138	0.061

[a] CBCT indicates cone beam computed tomography; kVp, kilovolt peak; LT, left; mA, milliamperage; RT, right; SD, standard deviation; Zygo LT, zygomatic left; Zygo RT, zygomatic right.



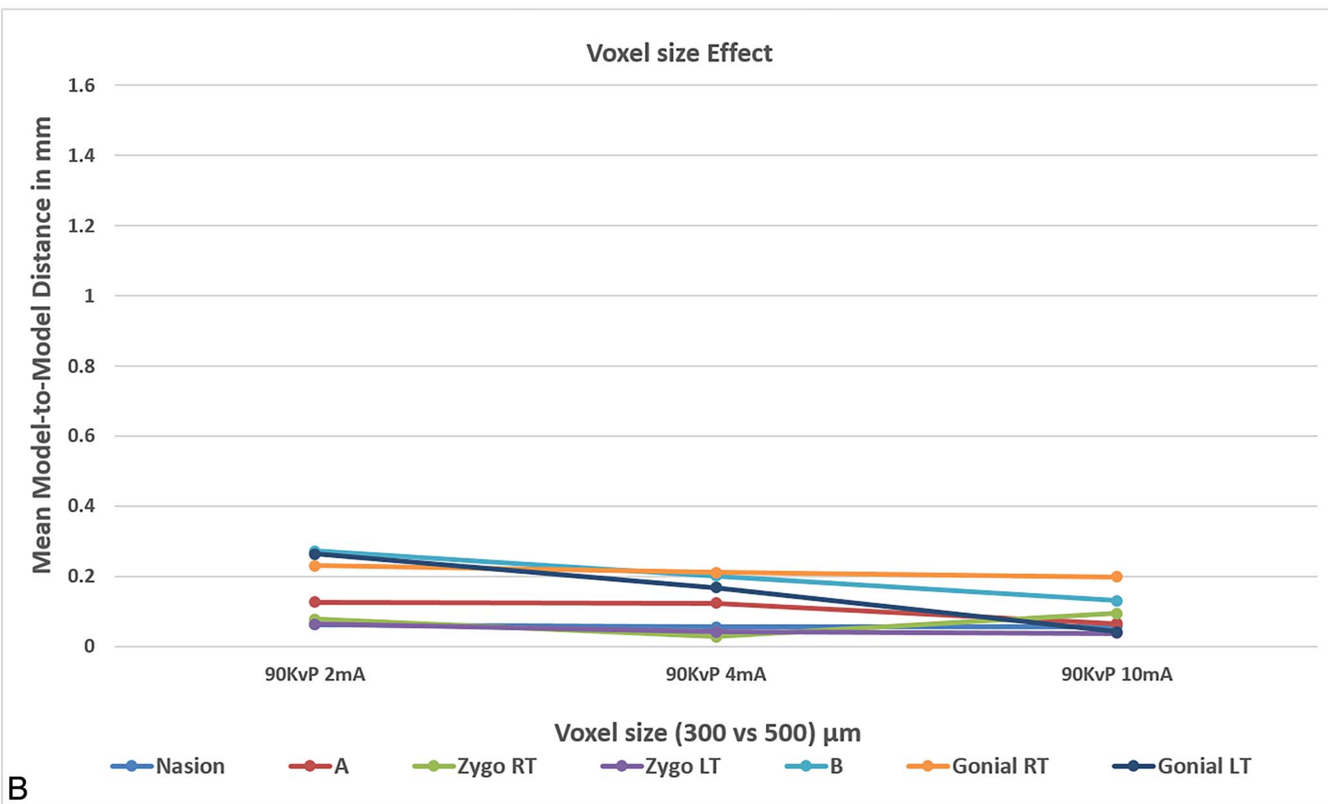


Figure 7. (A) Color-coded maps demonstrating voxel size effects on superimposed CBCTs with changed voxel size parameters (300 vs 500) μm. (A) 90 kVp with 2 mA; (B) 90 kVp with 4 mA; (C) 90 kVp with 10 mA. (B) Graphic showing two different voxel size settings compared with model-to-model distance. CBCT indicates cone beam computed tomography; kVp, kilovolt peak; mA, milliamperage.

Table 5. Mean Differences and Standard Deviations in mm Between Registered CBCTs When Changing Voxel Size Settings (300 vs 500) μm. (A) 90 kVp With 2 mA; (B) 90 kVp With 4 mA; (C) 90 kVp With 10 mA[a]

	(A)				(B)				(C)			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Nasion	0	0.153	0.063	0.033	0	0.149	0.056	0.038	0.001	0.057	0.057	0.026
A	0.014	0.272	0.127	0.055	0.077	0.188	0.124	0.024	0.166	0.066	0.066	0.04
Zygo RT	0.002	0.163	0.078	0.031	0.001	0.078	0.028	0.019	0.243	0.095	0.095	0.05
Zygo LT	0	0.191	0.065	0.035	0	0.116	0.043	0.031	0.127	0.038	0.038	0.027
B	0.202	0.373	0.273	0.029	0.059	0.393	0.202	0.087	0.196	0.131	0.131	0.026
Gonial RT	0.004	0.572	0.231	0.112	0.002	0.425	0.212	0.077	0.395	0.2	0.2	0.066
Gonial LT	0.002	0.564	0.264	0.139	0.002	0.383	0.169	0.084	0.106	0.042	0.042	0.028

[a] CBCT indicates cone beam computed tomography; kVp, kilovolt peak; LT, left; mA, milliamperage; RT, right; SD, standard deviation; Zygo LT, zygomatic left; Zygo RT, zygomatic right.

of photons through slices which caused less noise along with an image with fewer details.[26,27]

The current study attempted to get an idea about the role that each factor played separately in image quality and accuracy of the Dolphin 3D voxel-based superimposition method. The relationship among all these factors was intimate and something to be kept in mind. Changing any of them (kVp and mA) will have an impact on the other one. The methodology used was complicated and included multiple steps. Most of the steps were automated which helped getting more repeatable results. However, some of the differences could have been due to the steps after registration; for example, having a noisy surface model could have added to the differences between the two surfaces.

CONCLUSIONS

- Using different CBCT settings can affect the accuracy of the voxel-based superimposition method. This is particularly the case when using low kVp values. Changes in mA or voxel sizes did not significantly interfere with the superimposition outcome.

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