Int. J. Oral Maxillofac. Surg. 2016; 45: 662–669
http://dx.doi.org/10.1016/j.ijom.2015.12.006, available online at http://www.sciencedirect.com

International Journal of Oral & Maxillofacial Surgery

Research Paper
Imaging

Three-dimensional maxillary and mandibular regional superimposition using cone beam computed tomography: a validation study

L. Koerich[1], D. Burns[2], A. Weissheimer[3], J. D. P. Claus[4]
[1]International Dental Program, Virginia Commonwealth University, Virginia, USA; [2]Department of Prosthodontics, Virginia Commonwealth University, Virginia, USA; [3]Department of Orthodontics, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil; [4]Department of Oral and Maxillofacial Surgery, Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

L. Koerich, D. Burns, A. Weissheimer, J. D. P. Claus: Three-dimensional maxillary and mandibular regional superimposition using cone beam computed tomography: a validation study. Int. J. Oral Maxillofac. Surg. 2016; 45: 662–669.

Abstract. This study aimed to validate a novel method for fast regional superimposition of cone beam computed tomography (CBCT) scans. The method can be used with smaller field of view scans, thereby allowing for a lower radiation dose. This retrospective study used two dry skulls and secondary data from 15 patients who had more than one scan taken using the same machine. Two observers tested two types of regional voxel-based superimposition: maxillary and mandibular. The registration took 10–15 s. Three-dimensional surface models of the maxillas and mandibles were generated via standardized threshold segmentation, and the accuracy and reproducibility of the superimpositions were assessed using the iterative closest point technique to measure the root mean square (RMS) distance between the images. Five areas were measured and a RMS ≤ 0.25 was considered successful. Descriptive statistics and the intra-class correlation coefficient (ICC) were used to compare the intra-observer measurement reproducibility. The ICC was $\geq$0.980 for all of the variables and the highest RMS found was 0.241. The inter-observer reproducibility was assessed case by case and was perfect (RMS 0) for 68% (23 out of 34) of the superimpositions done and not clinically significant (RMS ≤ 0.25) for the other 32%. The method is fast, accurate, and reproducible and is an alternative to cranial base superimposition.

Keywords: cone-beam CT; three-dimensional image; 3D image registration; CBCT superimposition; 3D image fusion.

Accepted for publication 8 December 2015
Available online 12 January 2016

Cone beam computed tomography (CBCT) has become a very popular diagnostic tool, with several applications in dentistry. One of these is the superimposition of CBCT scans, which has become the state-of-the-art technique for the assessment of treatment outcome, for which CBCT is indicated. It allows clinicians and researchers to better understand the treatment outcomes and improve techniques.

In medical imaging, the process of spatially superimposing three-dimensional

(3D) images is called image superimposition, image registration, or fusion.[1] There are three basic types of superimposition that clinicians need to know: (1) point–landmark-based, (2) surface-based, and (3) voxel-based.[2] The latter and most efficient method compares non-changing reference structures in volumetric data voxel by voxel, does not depend on landmark identification as in the point–landmark-based method, and is not limited by segmentation errors as in surface-based methods.

In orthodontics and oral and maxillofacial surgery, the superimposition of CBCT scans with a large field of view (FOV) has been used to assess orthopedic and surgical outcomes.[3–5] Cevidanes et al. were the first to introduce a voxel-based method for the superimposition of CBCT scans into dentistry; they used the cranial base as the reference to superimpose two or more CBCT scans obtained from non-growing patients.[3] Despite its excellent research application, this method involves the use of different software programs and is time-consuming. Nada et al., using a different software program, tested voxel-based superimposition using either the anterior cranial base or the left zygomatic arch as the reference in non-growing patients.[6] The FOV of the CBCT and the radiation exposure could be reduced slightly with the zygomatic arch superimposition. Despite the good results using each structure as the reference, the method used for each superimposition was also time-consuming (30–40 min).

Most of the studies mentioned above were performed to understand changes in the maxilla and/or the mandible in relation to the cranial base in large FOV scans. There are two problems with this technique: (1) a large FOV is needed to appreciate localized changes in the maxilla and (2) even with a large FOV, the changes in the mandible are not assessed accurately because the mandible can have a different position in each scan. The issue is that a large FOV exposes the patient to a higher radiation dose compared to the use of a medium or small FOV.[7] Therefore, a different method that allows fast, reliable, and accurate 3D regional superimposition of CBCT scans with smaller FOVs and a lower radiation dose is needed.

As stated previously, the voxel-based technique is not new, however superimposition using the maxilla and the mandible as the reference is. Therefore, the aim of this study was to test the accuracy and the reproducibility of a regional superimposition method for the maxilla and mandible in non-growing patients using CBCT.

Materials and methods

Subjects and CBCT scan

The study was approved by the necessary ethics committee. The sample for this retrospective study comprised the CBCT files for two dry skulls obtained from the Oral Diagnostic Science Department of Virginia Commonwealth University and secondary data from 15 patients who had undergone either surgical treatment (coronectomy of wisdom teeth and bone grafts) and/or orthodontic treatment at a private practice. The CBCT scans were taken between April 2009 and March 2015 and the patients ranged in age from 27 to 65 years. All of the patients had either full dentitions or were partially edentulous. Inclusion criteria for the human subjects were (1) non-growing patient, with (2) two CBCT scans (T1 and T2) taken using the same machine and with the same voxel size (0.25 mm). Exclusion criteria were (1) same patient with CBCT scans from different machines, (2) CBCT scans with a different voxel size between T1 and T2.

The dry skulls images were acquired with a Kodak Carestream 9300 (Carestream Health Inc., Rochester, NY, USA) and 13.5 × 17 cm FOV, scan time of 11.3 s, set at 85 kVp, 4 mA, and 0.3-mm voxel size. Two images of each dry skull were taken, modifying its position between T1 and T2. These images were used as a gold standard since there was no bony change between T1 and T2. The patient images were acquired with an i-CAT scanner (Imaging Sciences International LLC, Hatfield, PA, USA) and 16 × 13 cm FOV, scan time of 27 s, set at 120 kVp, 8 mA, and isotropic 0.25-mm voxel size. The DICOM (Digital Imaging and Communication in Medicine) files were imported into OnDemand 3D v1.0.10.5261 (Cybermed Inc., Seoul, Korea). The T2 scan was taken between 4 and 24 months (average 12.3 months) after T1.

3D image processing

A summary of the method is given in Fig. 1. One observer cropped the CBCT files from T1 and T2 to simulate a 10 × 5 cm FOV scan, obtaining a significant amount of the maxillary and mandibular area. The crops were done as shown in Fig. 2; this resulted in a total of four images: T1 mandible, T1 maxilla, T2 mandible, and T2 maxilla. The software used allows the clinician to crop in any dimension, and the inferosuperior crops are done precisely by selecting the number of slices that the user wants to keep. In the present study, 200 slices were used to simulate 5 cm of height (200 × 0.25 mm = 5 cm). The software

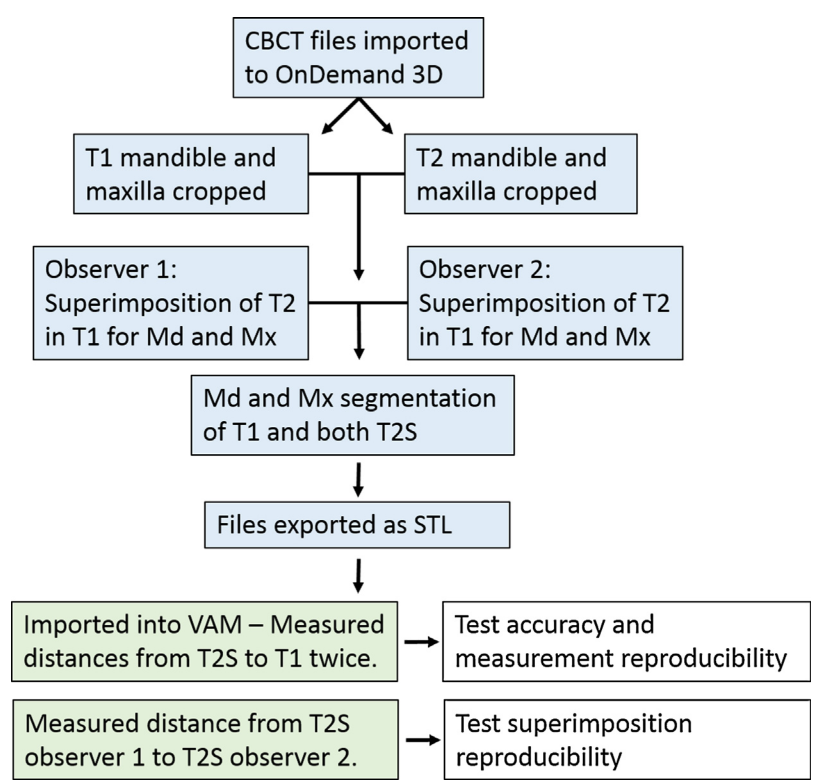

Fig. 1. Flowchart of the method. The blue boxes are steps done using OnDemand 3D and the green boxes are steps done using VAM (Md, mandible; Mx, maxilla; T2S, T2 superimposed).

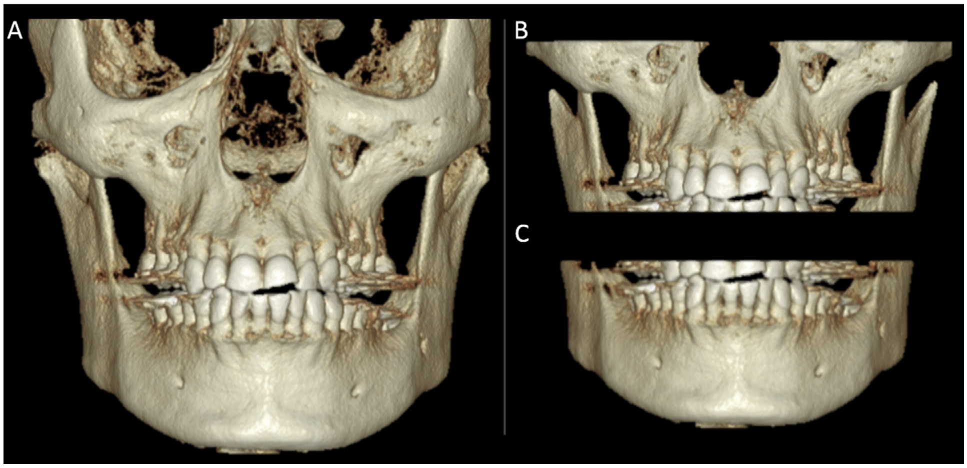

Fig. 2. (A) Full skull before crop. (B) Maxilla cropped, and (C) mandible cropped. Each image was cropped to simulate a 10 × 5 cm CBCT. The maxillary crop included the upper teeth, alveolar process, and part of the zygomatic bone, avoiding the inclusion of the zygomatic arch as a whole. The mandibular crop included the lower teeth, corpus, angle, and part of the ramus.

does not allow precise cropping in the anteroposterior dimension, therefore the CBCT scans were approximately 10 cm. The images were saved in the software database.

Two observers (L.K. and A.W.) attempted to perform the regional superimposition independently. For the mandibular superimposition, the cropped mandibular files from T1 and T2 were opened using the 'fusion' tab of the software. The fusion module allows the observer to manually move T2 as close as possible to the position of T1 and also allows the observer to do an automatic voxel-based superimposition. The superimposition process took approximately 10–15 s. The software reads the voxels from the whole scan in T1 and tries to match them with a similar area in T2. Although the software had a tool to focus on the voxels of a specific region of interest, this was not needed in the present study. For the maxillary superimposition, the stable areas included in the crop were the zygomatic process of the maxilla and the palate. For the mandible, the stable areas were the symphysis, corpus, and part of the ramus.

After the superimposition had been done (Fig. 3), the T2 file in its new orientation was saved (T2 superimposed, T2S). One observer (L.K.) was responsible for segmenting T1 and T2S mandibular files using the '3D picker' tool inside the '3D' module. All the segmentations were standardized at 381–382 grey levels and the segmented files were exported in STL format (Standard Tessellation Language) using the software parameters of 0.005 reduction error and a smooth of 1. The same steps were done for the maxillary cropped area.

One observer imported all six STL files (T1 maxilla and mandible and T2S maxilla and mandible for each observer) into VAM (Canfield Scientific, Fairfield, NJ, USA) and performed measurements with the iterative

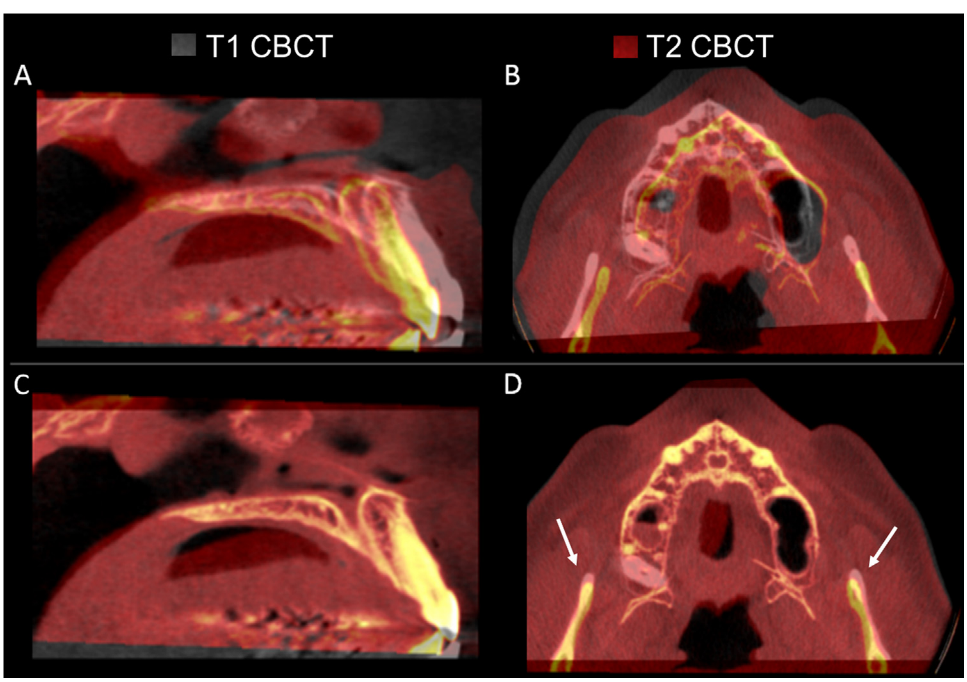

Fig. 3. (A) Sagittal and (B) axial views of the maxilla before superimposition, and the same (C) sagittal and (D) axial views after the maxillary superimposition. Note that in the maxillary area, the T1 and T2 images match, while in the mandible (white arrows), they do not.

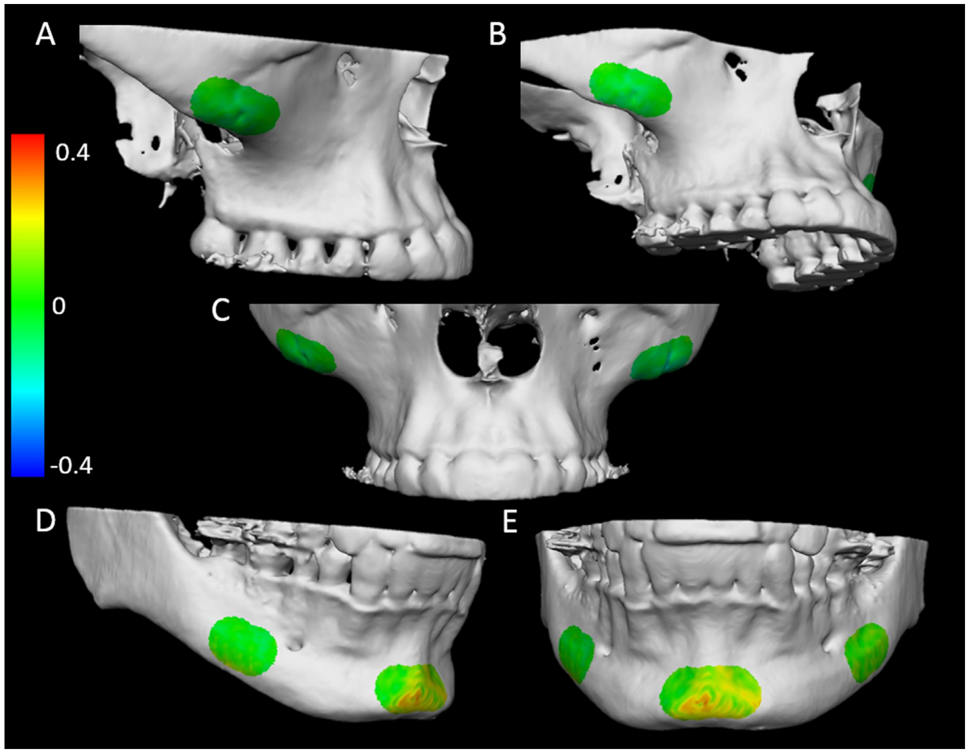

Fig. 4. Areas of interest measured and colour-coded map ranging from 0.4 to −0.4 mm. (A) Lateral view of the maxilla; (B) latero-inferior view of the maxilla; (C) anterior view of the maxilla; (D) lateral view of the mandible; (E) anterior view of the mandible.

closest point (ICP) technique. The ICP measures the smallest distance between two surfaces, providing the root mean square (RMS). A RMS value smaller than 0.25 mm (the voxel size) and errors for living subjects comparable to those found with the dry skulls were required to prove that the superimposition method is accurate. The aim was to perform the measurements in stable areas not influenced by the alveolar changes. In the maxilla, measurements were made at the lower border of the zygomatic alveolar crest, anterior and posterior to the zygomatic maxillary suture (Fig. 4A–C). In the mandible, the measurements were made at the basal bone of the chin prominence and distal to the mental foramens on both sides (Fig. 4D, E).

To prove that the method is reproducible, the ICP was used to measure the distances between T2S of operator 1 and T2S of operator 2. The RMS value was obtained: the distance between the models should be smaller than 0.25, while 0 would be considered perfect. The measurements were repeated by the same operator after 10 days to ensure reproducibility. The results were exported to an excel spreadsheet.

Statistical analysis

The statistical analyses were done using IBM SPSS Statistics software version 22.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics for the RMS were obtained separately for the dry skulls and the human subjects. Intra-examiner agreement for the measurements was assessed by means of the intra-class correlation coefficient (ICC) and descriptive statistics with mean differences and confidence intervals set at 95%, and included the living subjects and dry skulls. The values for inter-examiner reproducibility are reported individually.

Results

Table 1 shows the descriptive analysis of the cases. The highest RMS found for the dry skulls was 0.195 and the highest mean RMS was 0.184. For the human subjects, the highest RMS was 0.241 and the highest mean was 0.105.

Table 2 shows the ICC and descriptive results. All the values for the ICC were higher than 98%, showing the excellent reproducibility of the measurements. The descriptive results confirmed the excellent reproducibility of the measurements, with all mean values smaller than -0.005 ± -0.013.

Table 3 shows the case-by-case analysis of method reproducibility; RMS was compared between the two observers. The results for the two dry skulls were perfect for the mandible and maxilla (RMS = 0). For the human subjects, the result was

Table 1. Descriptive statistics for the dry skulls and human subjects.[a]

	Min	Max	Mean	SD
Dry skulls				
Mandible right	0.075	0.099	0.087	0.017
Chin	0.021	0.152	0.087	0.093
Mandible left	0.017	0.178	0.098	0.114
Maxilla right	0.176	0.192	0.184	0.011
Maxilla left	0.170	0.195	0.183	0.018
Human subjects				
Mandible right	0.040	0.241	0.105	0.070
Chin	0.031	0.154	0.100	0.044
Mandible left	0.042	0.176	0.087	0.041
Maxilla right	0.023	0.160	0.072	0.038
Maxilla left	0.045	0.160	0.092	0.040

Min, minimum; Max, maximum; SD, standard deviation.
[a] Numbers are the root mean square (RMS) in millimeters.

Table 2. Intra-class correlation coefficient (ICC) and Bland–Altman to test the reproducibility of the measurements.

	ICC	Bland–Altman	
		Mean ± SD	95% CI
Mandible right	0.994	−0.003 ± 0.011	−0.008 to 0.003
Chin	0.996	0.001 ± 0.006	−0.001 to 0.004
Mandible left	0.980	−0.005 ± 0.013	−0.012 to 0.001
Maxilla right	0.994	−0.002 ± 0.009	−0.006 to 0.003
Maxilla left	0.987	0.002 ± 0.011	−0.004 to 0.008

SD, standard deviation; CI, confidence interval.

Table 3. Case-by-case analysis showing the RMS difference in each area of interest between T2S by observer 1 and T2S by observer 2.

Case	Mandible right	Chin	Mandible left	Maxilla right	Maxilla left
DS1	0	0	0	0	0
DS2	0	0	0	0	0
1	0	0	0	0.047	0.030
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0.007	0.014	0.008	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0.011	0.004
10	0	0	0	0.009	0.011
11	0	0	0	0.009	0.024
12	0.026	0.012	0.020	0	0
13	0.008	0.012	0.019	0	0
14	0.003	0.005	0.009	0.008	0.010
15	0.006	0.009	0.008	0.015	0.032

RMS, root mean square; T2S, T2 superimposed; DS, dry skull.

perfect for 67% (10 out of 15) of the mandibles and 60% (9/15) of the maxillas. Overall the result was perfect for 68% (23/34) of the superimpositions. For the cases in which the superimposition was not perfect, the highest RMS found was 0.026 in the mandible (case 12) and 0.047 in the maxilla (case 1).

Discussion

This study proposes a voxel-based maxillary and mandibular superimposition. Choi and Mah introduced a fast cranial base superimposition method and presented three clinical cases.[8] Lee et al. validated the former methodology using a dry skull,[9] while Weissheimer et al. validated it for growing and non-growing patients.[10] The process was also fast (taking 10–15 s) and voxel-based. Other methods have been proposed for the superimposition of CBCT scans. The point–landmark-based method was reported by McCance et al. in 1992.[11] They used five landmarks to superimpose conventional CT scans before and after orthognathic surgery. This method is not used, probably because of the lack of consistency in selecting the landmarks.[12] The surface-based method is an alternative to voxel-based methods; this method has been reported to be highly successful based on a study by Almukhtar et al., who compared voxel-based and surface-based superimpositions of the cranial base and found no statistically significant difference between the methods.[13]

Out of 19 identified longitudinal studies performed in the last 5 years that have tried to evaluate changes in the maxilla, mandible, or maxillary sinus, only three used a method of superimposition that could likely be reproducible.[14–32] Economopoulos et al. presented a superimposition method to quantify volume differences after bone augmentation; however, the authors did not specify the area used for superimposition.[18] Ahmad et al. used surface-based mandibular superimposition to evaluate mandibular alveolar resorption in edentulous patients.[14] Despite the innovative methodology, the authors did not show by either colour maps or statistical analysis that the method is accurate or reproducible. The study by Meloni et al. was the only one to use a validated method: a voxel-based cranial base superimposition was used to evaluate changes in the maxilla after extraction and socket preservation.[24]

As well as reducing the FOV and significantly reducing the radiation dose to which the patient is exposed,[7] the technique presented here proved to be accurate in the superimposition of the maxilla and the mandible. The results obtained with living subjects (RMS ≤ 0.105) were similar to those obtained with the dry skulls (RMS ≤ 0.184). The ICC was excellent ($\geq$0.980) for all measured areas, ensuring the reproducibility of the measurements. In addition, it can be said that the method is reproducible because the RMS for 68% of the cases was 0. For the cases that were not perfect, the highest RMS was 0.047, which has no clinical relevance. Although the segmentation process was standardized with the selection of the same grey level interval, small differences in the segmentation could have resulted from different grey level intensity due to artifacts during the CBCT scan process, which could have had some influence on the accuracy of segmentation.[33] Thus, it is assumed that the error found in the present superimposition method is in part due to the small differences in segmentations and in part due to the superimposition process itself. Nevertheless, the method error has no clinical significance.

Despite the similar results found by Almukhtar et al. when comparing voxel-based and surface-based superimposition,[13] there are two main advantages of the voxel-based method that should be highlighted. First, there is no need to create a surface-based model, which demands time and one extra file, probably requiring the use of different software. Second, the voxel-based method allows easy assessment of the inner surfaces, since the superimposed structures can be viewed in the multiplanar slices (axial, sagital and coronal). In the surface-based technique only the outer surfaces can be evaluated since the multiplanar reconstruction is not superimposed. Therefore, with surface models it is much more difficult to assess changes where the density of the bone is not similar (immediately after sinus lift, socket preservation, or bone grafts), because the segmentation process will be affected. Internal anatomical structures such as the mandibular canal, teeth roots, or small bone defects are difficult to differentiate with accuracy in order to segment and create virtual surface models for superimposition. Furthermore, this process is too time-consuming.

The highest mean RMS of 0.105 found in human subjects in the present study is slightly smaller than the absolute means found in other studies. Nada et al., using a voxel size of 0.4 mm, found values as low as 0.3 ± 0.12 mm for the cranial base superimposition and 0.17 mm for the left zygomatic arch registration.[6] Lee et al., using a voxel size of 0.2 mm and one dry skull with 24 different orientations, found a mean error of 0.396 ± 0.142 mm for the cranial base superimposition.[9] In their study, titanium markers were used to facilitate landmark identification instead of colour maps. Weissheimer et al. did not provide a statistical analysis for their research, but showed a cranial base superimposition error of less than 0.5 mm through colour maps.[10] The voxel size in their study was 0.25 mm, the same as used in the present study. Almukhtar et al. did not specify the voxel size; they evaluated surface- and voxel-based superimposition of the cranial base and the results were 0.047 ± 0.259 mm and 0.050 ± 0.206 mm, respectively.[13] The result of the present study being slightly smaller than those of the other studies is probably because of the smaller voxel size or the rigorous segmentation process used in this study. Nevertheless, all of the studies, including that presented here, show a method error that has no clinical relevance; these methods can therefore be applied in future research.

As well as being very accurate and reproducible, the main advantages of the method presented here are the reduction in radiation to which the patient is exposed and the speed at which the superimposition can be done. The main disadvantages are that this process does not work without cropping the maxilla or mandible and that the software is only available commercially and is not open-source, as used by Cevidanes et al.[3] Another aspect that is important to highlight is that the cropped images purposely included stable areas and not only the alveolar region. It is interesting to note that if the cranial base had been included in the scan, the regional superimposition would not have worked, even if the tool to select the voxels from a specific region of interest had been used. In this study, the structures were not measured as a whole piece because the patients had undergone procedures between time points (bone grafts, extractions, implant placement, root canal treatment, and others) and this could have affected the measurements. Measurements were taken from opposing areas to ensure that the superimposition was done correctly everywhere.

This study aimed to validate a method for 3D regional superimposition of CBCT scans of non-growing patients. It would be useful to develop the same idea with growing patients, especially to better understand mandibular and maxillary growth. Another idea is to test the method with different scans or voxel sizes between time points, because in the analysis of long-term data (10 years or more), with the fast pace at which technology advances, it is most likely that patient CBCT scans will be taken with different and better machines.

The use of the maxilla or mandible as the reference for regional superimposition instead of the cranial base allows accurate 3D assessment while decreasing the radiation dose to the patient due the smaller FOV. This superimposition method can be applied but is not limited to several clinical evaluations in implantology, such as bone grafting (Fig. 5), the accuracy of implant placement, sinus lift, and alveolar resorption. It could also be used to determine the absence of alveolar growth in the 'aesthetic zone' of the anterior region of the maxilla, helping the clinician to establish the best time to place the implant in young adults. Other methods to assess growth include hand–wrist X-rays, which may not be precise in providing such information,[34] and sequential cephalometric examinations, which have inherent issues such as the magnification and superimposition of structures that affect the tracing and diagnosis.[35] Other possible applications are the assessment of condylar resorption or hyperplasic growth, healing of endodontic lesions, and tooth movements in orthodontic surgical cases, or other situations for which CBCT is indicated.

Independent of the software used and the time taken to process the superimposition, voxel-based superimposition appears to represent the gold standard when the cranial base is used as the reference and will probably also

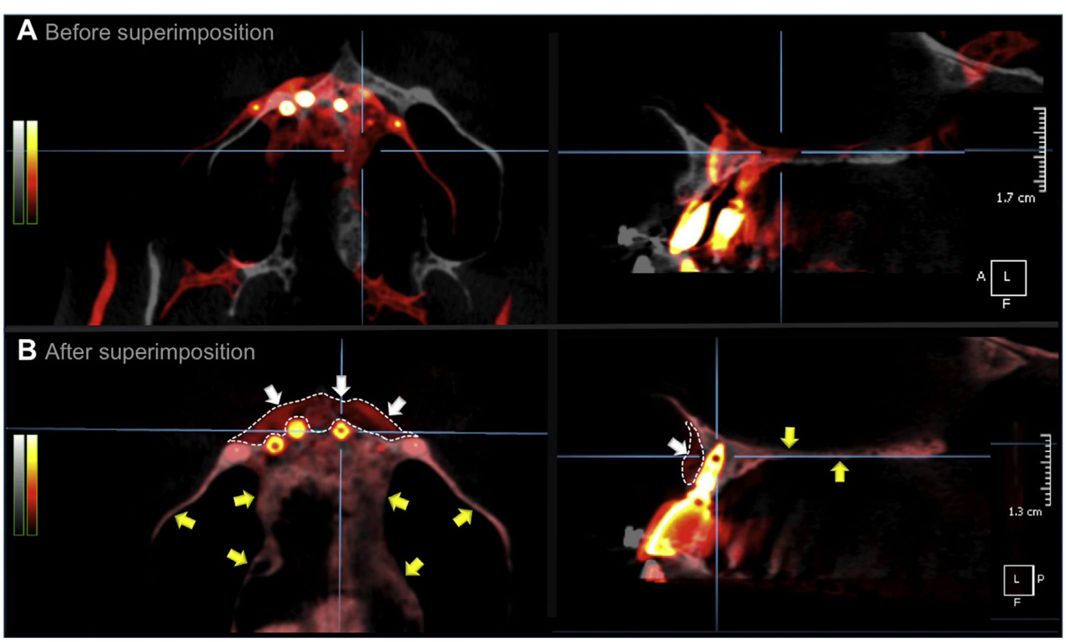

Fig. 5. (A) Axial and sagittal views of the CBCT scans before superimposition. (B) The same views after superimposition. The yellow arrows show matching of the grey and red borders of the T1 and T2 images. The white arrows indicate the areas where the superimposition does not match as a result of the patient having had implants and a bone graft placed in the area (dotted line).

represent the gold standard for regional superimposition in the future. This will help to standardize methods and make comparisons between different studies easier.

Funding

This study was supported by the A. D. Williams Funds (award number UL1RR031990) from the National Center for Research Resources and NIH Roadmap for Medical Research, National Institutes of Health.

Competing interests

None declared.

Ethical approval

The work was approved by the Institutional Review Board of Virginia Commonwealth University (number HM20004882).

Patient consent

Not required.

Acknowledgements. The authors would like to thank Dr. Laurie Carter for providing part of the data for this study, Dr. Al M. Best (PhD) for his help with the statistical analysis, Dr. John Gunsolley for the technological support, Dr. Diandra Santos Luz for the technical and writing assistance and Cybermed Inc. for providing the software for this research.

References

1. Li G, Xie H, Ning H, Capala J, Arora BC, Coleman CN, et al. A novel 3D volumetric voxel registration technique for volume-view-guided image registration of multiple imaging modalities. *Int J Radiat Oncol Biol Phys* 2005;**63**:261–73. http://dx.doi.org/10.1016/j.ijrobp.2005.05.008.
2. Maes F, Collignon A, Vandermeulen D, Marchal G, Suetens P. Multimodality image registration by maximization of mutual information. *IEEE Trans Med Imaging* 1997;**16**:187–98. http://dx.doi.org/10.1109/42.563664.
3. Cevidanes LH, Bailey LJ, Tucker Jr GR, Styner MA, Mol A, Phillips CL, et al. Superimposition of 3D cone-beam CT models of orthognathic surgery patients. *Dentomaxillofac Radiol* 2005;**34**:369–75. http://dx.doi.org/10.1259/dmfr/17102411.
4. De Clerck H, Nguyen T, de Paula LK, Cevidanes L. Three-dimensional assessment of mandibular and glenoid fossa changes after bone-anchored class III intermaxillary traction. *Am J Orthod Dentofacial Orthop* 2012;**142**:25–31. http://dx.doi.org/10.1016/j.ajodo.2012.01.017.
5. de Paula LK, Ruellas AC, Paniagua B, Styner M, Turvey T, Zhu H, et al. One-year assessment of surgical outcomes in class III patients using cone beam computed tomography. *Int J Oral Maxillofac Surg* 2013;**42**:780–9. http://dx.doi.org/10.1016/j.ijom.2013.01.002.
6. Nada RM, Maal TJ, Breuning KH, Berge SJ, Mostafa YA, Kuijpers-Jagtman AM. Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches. *PLoS ONE* 2011;**6**:e16520. http://dx.doi.org/10.1371/journal.pone.0016520.
7. Bornstein MM, Scarfe WC, Vaughn VM, Jacobs R. Cone beam computed tomography in implant dentistry: a systematic review focusing on guidelines, indications, and radiation dose risks. *Int J Oral Maxillofac Implants* 2014;**29**(Suppl):55–77. http://dx.doi.org/10.11607/jomi.2014.uppl.g1.4.
8. Choi JH, Mah J. A new method for superimposition of CBCT volumes. *J Clin Orthod* 2010;**44**:303–12.
9. Lee JH, Kim MJ, Kim SM, Kwon OH, Kim YK. The 3D CT superimposition method using image fusion based on the maximum mutual information algorithm for the assessment of oral and maxillofacial surgery treatment results. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012;**114**:167–74. http://dx.doi.org/10.1016/j.tripleo.2011.06.003.
10. Weissheimer A, Menezes LM, Koerich L, Pham J, Cevidanes LH. Fast three-dimensional superimposition of cone beam computed tomography for orthopaedics and orthognathic surgery evaluation. *Int J Oral Maxillofac Surg* 2015;**44**:1188–96. http://dx.doi.org/10.1016/j.ijom.2015.04.001.
11. McCance AM, Moss JP, Wright WR, Linney AD, James DR. A three-dimensional soft tissue analysis of 16 skeletal class III patients following bimaxillary surgery. *Br J Oral Maxillofac Surg* 1992;**30**:221–32.
12. Kim YR, Park Y, Koerich de Paula L, Conley RS. 3D assessment of orthognathic surgery outcomes. In: Kapila S, editor. *Cone beam computed tomography in orthodontics: indications, insights and innovations.*. Wiley-Blackwell; 2014. p. 463–84.
13. Almukhtar A, Ju X, Khambay B, McDonald J, Ayoub A. Comparison of the accuracy of voxel based registration and surface based registration for 3D assessment of surgical change following orthognathic surgery. *PLOS ONE* 2014;**9**:e93402. http://dx.doi.org/10.1371/journal.pone.0093402.
14. Ahmad R, Abu-Hassan MI, Li Q, Swain MV. Three dimensional quantification of mandibular bone remodeling using standard tessellation language registration based superimposition. *Clin Oral Implants Res* 2013;**24**:1273–9. http://dx.doi.org/10.1111/j.1600-0501.2012.02566.x.
15. Baciut M, Hedesiu M, Bran S, Jacobs R, Nackaerts O, Baciut G. Pre- and postoperative assessment of sinus grafting procedures using cone-beam computed tomography compared with panoramic radiographs. *Clin Oral Implants Res* 2013;**24**:512–6. http://dx.doi.org/10.1111/j.1600-0501.2011.02408.x.
16. Dellavia C, Speroni S, Pellegrini G, Gatto A, Maiorana C. A new method to evaluate volumetric changes in sinus augmentation procedure. *Clin Implant Dent Relat Res* 2014;**16**:684–90. http://dx.doi.org/10.1111/cid.12058.
17. Diez GF, Fontao FN, Bassi AP, Gama JC, Claudino M. Tomographic follow-up of bone regeneration after bone block harvesting from the mandibular ramus. *Int J Oral Maxillofac Surg* 2014;**43**:335–40. http://dx.doi.org/10.1016/j.ijom.2013.08.010.
18. Economopoulos TL, Asvestas PA, Matsopoulos GK, Molnar B, Windisch P. Volumetric difference evaluation of registered three-dimensional pre-operative and post-operative CT dental data. *Dentomaxillofac Radiol* 2012;**41**:328–39. http://dx.doi.org/10.1259/dmfr/94040044.
19. Hernandez-Alfaro F, Sancho-Puchades M, Guijarro-Martinez R. Total reconstruction of the atrophic maxilla with intraoral bone grafts and biomaterials: a prospective clinical study with cone beam computed tomography validation. *Int J Oral Maxillofac Implants* 2013;**28**:241–51. http://dx.doi.org/10.11607/jomi.2405.
20. Jung RE, Benic GI, Scherrer D, Hammerle CH. Cone beam computed tomography evaluation of regenerated buccal bone 5 years after simultaneous implant placement and guided bone regeneration procedures—a randomized, controlled clinical trial. *Clin Oral Implants Res* 2015;**26**:28–34. http://dx.doi.org/10.1111/clr.12296.
21. Karaca C, Er N, Gulsahi A, Koseoglu OT. Alveolar ridge preservation with a free gingival graft in the anterior maxilla: volumetric evaluation in a randomized clinical trial. *Int J Oral Maxillofac Surg* 2015;**44**:774–80. http://dx.doi.org/10.1016/j.ijom.2015.01.015.
22. Kim ES, Moon SY, Kim SG, Park HC, Oh JS. Three-dimensional volumetric analysis after sinus grafts. *Implant Dent* 2013;**22**:170–4. http://dx.doi.org/10.1097/ID.0b013e318273576.
23. Lin GH, Salemi JD, Kozloff KM, Chan HL, Wang HL. Measure bone volume and density changes of sites grafted with bone allografts and a titanium mesh on cone-beam computed tomography: a technique. *Implant Dent* 2015;**24**:362–6. http://dx.doi.org/10.1097/ID.0000000000000243.
24. Meloni SM, Tallarico M, Lolli FM, Deledda A, Pisano M, Jovanovic SA. Postextraction socket preservation using epithelial

connective tissue graft vs porcine collagen matrix. 1-year results of a randomised controlled trial. *Eur J Oral Implantol* 2015;**8**:39–48.
25. Miyamoto I, Funaki K, Yamauchi K, Kodama T, Takahashi T. Alveolar ridge reconstruction with titanium mesh and autogenous particulate bone graft: computed tomography-based evaluations of augmented bone quality and quantity. *Clin Implant Dent Relat Res* 2012;**14**:304–11. http://dx.doi.org/10.1111/j.1708-8208.2009.00257.x.
26. Naitoh M, Nabeshima H, Hayashi H, Nakayama T, Kurita K, Ariji E. Postoperative assessment of incisor dental implants using cone-beam computed tomography. *J Oral Implantol* 2010;**36**:377–84. http://dx.doi.org/10.1563/AAID-JOI-D-09-00080.
27. Nishida T, Takenouchi Y, Mori K, Ariji M, Nishida K, Ito K. Remodeling of autogenous bone grafts after osteotome sinus floor elevation assessed by limited cone beam computed tomography. *Int J Dent* 2013;**2013**:931708. http://dx.doi.org/10.1155/2013/931708.
28. Shalash MA, Rahman HA, Azim AA, Neemat AH, Hawary HE, Nasry SA. Evaluation of horizontal ridge augmentation using beta tricalcium phosphate and demineralized bone matrix: a comparative study. *J Clin Exp Dent* 2013;**5**:e253–9. http://dx.doi.org/10.4317/jced.51244.
29. Spin-Neto R, Stavropoulos A, Coletti FL, Faeda RS, Pereira LA, Marcantonio Jr E. Graft incorporation and implant osseointegration following the use of autologous and fresh-frozen allogeneic block bone grafts for lateral ridge augmentation. *Clin Oral Implants Res* 2014;**25**:226–33. http://dx.doi.org/10.1111/clr.12107.
30. Tadinada A, Ortiz D, Taxel P, Shafer D, Rengasamy K, Pendrys D, et al. CBCT evaluation of buccal bone regeneration in postmenopausal women with and without osteopenia or osteoporosis undergoing dental implant therapy. *J Prosthet Dent* 2015. http://dx.doi.org/10.1016/j.prosdent.2015.02.015.
31. Umanjec-Korac S, Wu G, Hassan B, Liu Y, Wismeijer D. A retrospective analysis of the resorption rate of deproteinized bovine bone as maxillary sinus graft material on cone beam computed tomography. *Clin Oral Implants Res* 2014;**25**:781–5. http://dx.doi.org/10.1111/clr.12174.
32. Zheng X, Teng M, Zhou F, Ye J, Li G, Mo A. Influence of maxillary sinus width on transcrestal sinus augmentation outcomes: radiographic evaluation based on cone beam CT. *Clin Implant Dent Relat Res* 2015. http://dx.doi.org/10.1111/cid.12298.
33. Weissheimer A, Menezes LM, Sameshima GT, Enciso R, Pham J, Grauer D. Imaging software accuracy for 3-dimensional analysis of the upper airway. *Am J Orthod Dentofacial Orthop* 2012;**142**:801–13. http://dx.doi.org/10.1016/j.ajodo.2012.07.015.
34. Verma D, Peltomaki T, Jager A. Reliability of growth prediction with hand–wrist radiographs. *Eur J Orthod* 2009;**31**:438–42. http://dx.doi.org/10.1093/ejo/cjp015.
35. Paula LK, Solon-de-Mello Pde A, Mattos CT, Ruellas AC, Sant'Anna EF. Influence of magnification and superimposition of structures on cephalometric diagnosis. *Dental Press J Orthod* 2015;**20**:29–34. http://dx.doi.org/10.1590/2176-9451.20.2.029-034.oar.

Address:
Leonardo Koerich
Virginia Commonwealth University
School of Dentistry
International Dental Program
520 North 12th Street
Richmond
VA 23298-0566
USA
Tel.: +1 919 998 9523
E-mails: lkoerich@gmail.com, koerichl@vcu.edu