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Precision and reliability of Dolphin 3-dimensional voxel-based superimposition

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Introduction: Superimposition of 2 cone-beam computed tomography images is possible by using landmarks, surfaces, or density information (voxel-based). Voxel-based superimposition is automated and uses the most image content, providing accurate results. Until recently, this superimposition was extremely laborious, but a user-friendly voxel-based superimposition has recently been introduced. Our aim was to evaluate the precision and reliability of Dolphin 3-dimensional voxel-based superimposition (Dolphin Imaging, Chatsworth, Calif). **Methods:** This was a retrospective study using existing scans of 31 surgical orthodontic patients with a mean age of 21 ± 8 years (range, 15-47 years). Each patient had a presurgical and a postsurgical scan taken within 12 months. Surgical patients were used since the reference area for superimposition was not affected by growth or surgical procedures. The volumes were superimposed using voxel-based methods from Dolphin Imaging and a tested method used previously. This method uses 2 open-source programs and takes about 3 hours to complete, whereas the Dolphin method takes under 5 minutes. The postsurgical scan was superimposed on the presurgical scan at the cranial base. Postsurgical registrations for both methods were compared with each other using the absolute closest point color map, with emphasis on 7 regions (nasion, A-point, B-point, bilateral zygomatic arches, and bilateral gonions). **Results:** Intraclass correlations showed excellent reliability (0.96). The mean differences between the 2 methods were less than 0.21 mm (voxel size, 0.38). The smallst difference was in the left zygomatic area at 0.09 ± 0.07 mm, and the largest was in the right gonial region at 0.21 ± 0.13 mm. **Conclusions:** Dolphin 3-dimensional voxel-based superimposition, a fast and user-friendly method, is precise and reliable. (Am J Orthod Dentofacial Orthop 2018;153:599-606)

Cephalometry has made a great impact in clinical orthodontics over the last 85 years since its invention by Broadbent in 1931. Superimposing serial cephalograms on relatively stable areas of the cranial base allows growth evaluation and treatment outcome assessments. Cephalometric analysis became popular, although with some accuracy and reliability limitations, mostly involving errors in landmark identification.[1,2] Researchers have concluded that every attempt to digitize the same landmark, even on the same cephalogram, will result in a different position.[3]

There has been a dramatic increase in the use of cone-beam computed tomography (CBCT) in dentistry over the last decade. CBCT provides more information than 2-dimensional (2D) images, and in certain cases, 3-dimensional (3D) images provide a more accurate and efficient diagnosis and treatment plan.[4-6]

The use of CBCT images in clinical orthodontics calls for a fast and accurate way to superimpose these images to evaluate craniofacial growth or treatment changes. Currently, there are 3 ways of superimposing 3D images: landmark, surface based, and voxel-based. Landmark superimposition is similar to 2D superimpositions, using anatomic landmarks or lines as references. Landmark identification on 3D images is much more complex than on 2D cephalometric radiographs,

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All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
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Submitted, April 2016; revised and accepted, July 2017.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2017.07.025

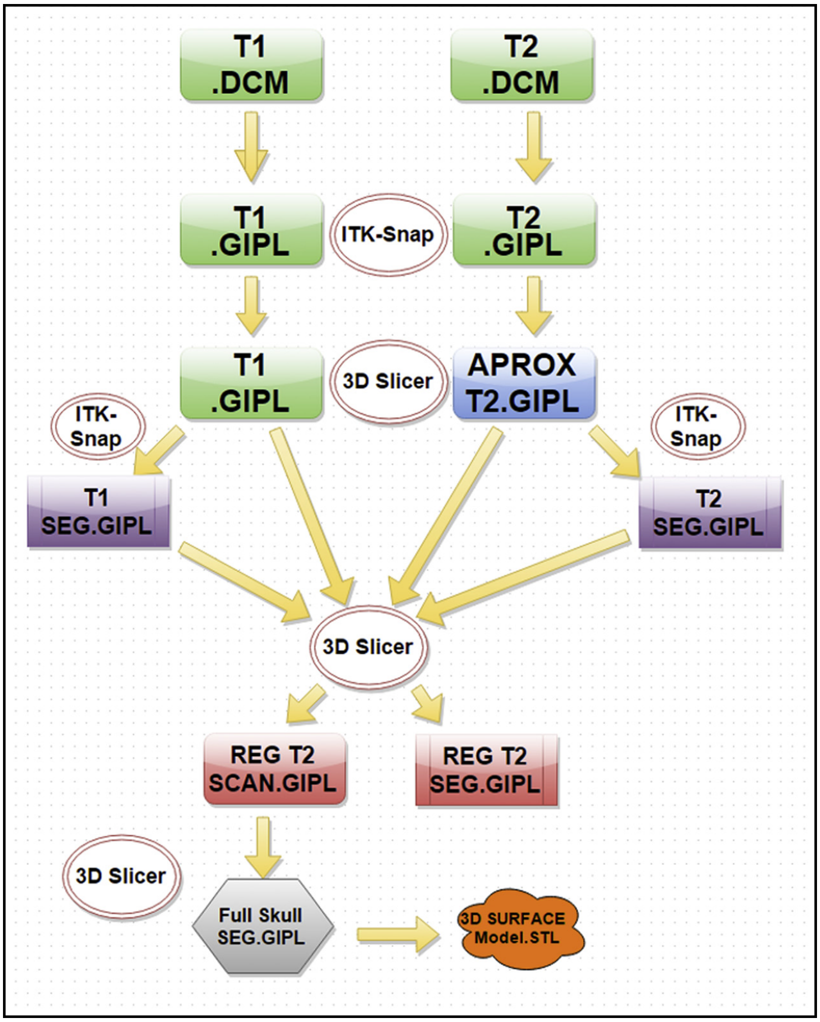

Fig 1. The method of Cevidanes et al[7,12-14] of voxel-based superimposition. The first step is changing the file format (from *DICOM* to *GIPL*) using ITK-SNAP software followed by manual approximation of T2 image (*APROX T2*) using 3D Slicer. The third step is the segmentation of the cranial base for each image (*T1* and *T2 SEG*), which was done by ITK-SNAP software to use it as the reference for the superimposition. The superimposition was done using the nonrigid voxel-based superimposition tool in 3D Slicer, and from that a registered T2 image (*REG T2*) was exported and used to create a surface model.

since landmark locations in 2D radiographs are usually easier to identify because of the nature of the images.[7-9] Surface-based superimposition deals with the shell covering the 3D structure and requires high-quality surface models for an accurate superimposition. Ong et al[10] used 3D surface models to quantify and visualize the immediate changes of the midface after rapid maxillary expansion. They concluded that the use of 3D surface models allows quantification and visualization of the 3D changes in the midfacial skeleton at anatomic sites distant from rapid maxillary expansion activation. Gkantidis et al[11] evaluated 5 surface superimposition techniques and found that using the anterior cranial base and foramen magnum gave the most accuracy, followed by the anterior cranial base and both zygomatic arches. Zygomatic arch superimposition has an additional advantage of being applicable in smaller field-of-view scans. Gkantidis et al also evaluated the accuracy of surface superimposition and landmark superimposition method, concluding that superimpositions based on landmarks were the least accurate, whereas 3D surface superimposition provides accurate, precise, and reproducible results.

Cevidanes et al[7,12-14] introduced a new superimposition method to the dental research field

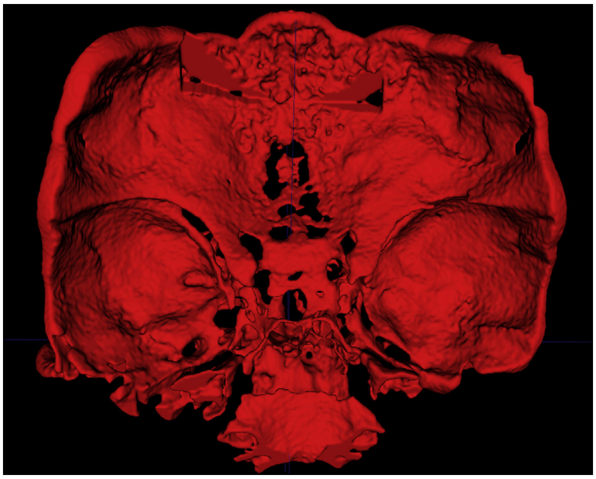

Fig 2. Cranial base segmentation using ITK-SNAP software showing the area used as a reference for the superimposition (*superior view*).

known as voxel-based superimposition, which has been widely used in various research purposes. Voxel-based superimposition matches the grayscale values of the voxels (density) to superimpose the CBCT images. Voxel-based superimposition is fully automated and uses the radiopacities and radioluscencies throughout the selected volume, removing the chance of operator error, which is the main disadvantage of the landmark superimposition method.

Almukhtar et al[15] compared surface-based superimposition with voxel-based superimposition and concluded that there were no significant statistical differences between the 2 methods; however, surface-based superimposition showed high variability in the mean distances between the surfaces compared with the voxel-based method.

The voxel-based superimposition method developed by Cevidanes et al[7,12-14] uses 2 open-source programs and takes about 3 hours to complete 1 superimposition. A commercially available imaging software, Dolphin 3D (version 11.8.06.15 premium; Dolphin Imaging, Chatsworth, Calif), recently introduced a user-friendly voxel-based superimposition, which can perform a 3D superimposition in less than 5 minutes. The aim of this study was to evaluate the precision and reliability of the Dolphin 3D voxel-based superimposition at the cranial base.

MATERIAL AND METHODS

This was a retrospective study using existing scans selected from the database of the Imaging Center at Case Western Rserve University in Cleveland, Ohio, and approved by its Institutional Review Board. The scans of 31 surgical orthodontic patients with a mean age of 21 ± 8 years (range, 15-47 years) were used. All subjects had 1-jaw or 2-jaw orthognathic surgery including Le-Fort I osteotomy, bilateral sagittal split osteotomy, or genioplasty. No reference area to be used for superimposition in this project was modified by surgical procedures. Presurgical scans (T1) were taken within 1 month before surgery, and postsurgical scans (T2) were taken within 12 months after surgery. All scans were taken using the CB MercuRay scanner (Hitachi Medical Systems America Inc, Twinsburg, OH) with the orthognathic surgical protocol set at 120 kVp, 15 mA, 12-in field of view, 4096 gray scale, 0.38 mm voxel size, and scan time of 9.5 seconds. Higher settings are used on the surgical protocol for thorough pathologic investigations and stereolithographic printing. The stereolithographic printing is used for surgical setup and splint fabrication. All files were originated and kept as DICOM files. Images of surgical patients were chosen for this project, since the reference areas for superimposition are unaltered by growth or the surgical procedures. The difference between T1 and T2 were always within 1 year, in a nongrowing population. This allowed a complete focus on the superimposition method, removing any biases related to growth.

In this study, the voxel-based superimposition method of Cevidanes et al[7,12,14] was used to evaluate the precision of the Dolphin 3D voxel-based superimposition. This method has been extensively used and published, and Dr Cevidanes has received funding from the National Institutes of Health for development of this method, followed by funding to use it to evaluate several types of craniofacial changes.

Traditionally, the comparison of different superimposition methods is performed by collecting and comparing landmark distances to see how close the methods are to each other.[16] The 3D technology used for the superimposition includes Cartesian coordinates for each voxel and a precise spatial location of the image. This way, starting both superimposition methods with T1 at the same location and maintaining it statically makes the final location of T2 the only variable. Knowing the exact final location of T2 allowed us to place both T2 scans together (method of Cevidanes et al[7,12-14] and Dolphin) and compare their differences comprehensively. In other words, it allowed us to evaluate the superimposition differences by placing 1 final location of T2 on top of the other. The final location of T2 is called the registered T2 and is represented as a surface model. The idea of using registered images is new to dental research. Recently, Ruellas et al[17] used registered 3D images to compare 2 regions of reference for maxillary regional superimposition.

The method of Cevidanes et al[7,12-14] uses 2 open-source programs and requires a computer with a fast

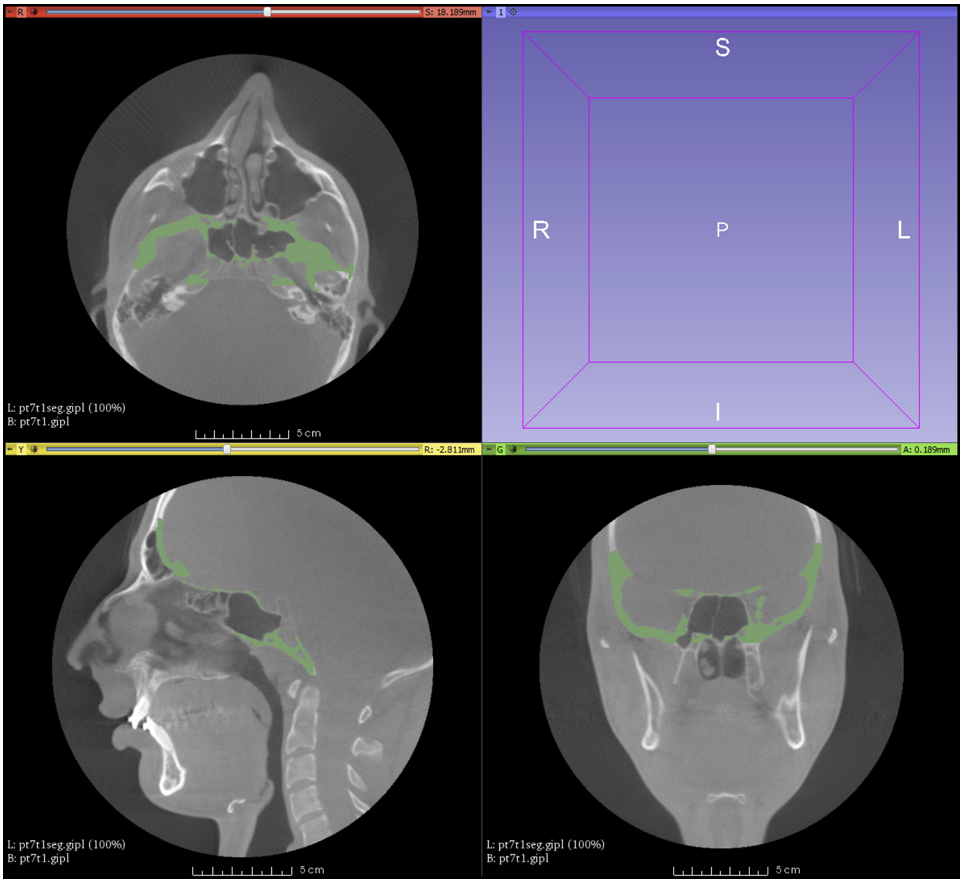

Fig 3. Voxel-based superimposition on the cranial base using 3D Slicer. The *green areas* in the slice views (axial, coronal, and sagittal) represent the reference structures that were used for the superimposition.

processor and a high-performance video card (Fig 1). For even higher efficiency during the process, the DICOM folder is converted to a file with a different file extension. Presurgical and postsurgical scans (DICOM) for each patient were opened using the ITK-SNAP software program (version 3.0.0; http://www.itksnap.org) and converted to Guys Imaging Processing Laboratory (GIPL) format for easy computing. The DICOM folder, which was originally 250 megabytes, after conversion to GIPL, turned into a file of about 100 megabytes. Another program, 3D Slicer (version 4.4.0; http://www.slicer.org), was then used to manually approximate the T2 CBCT image to the T1 image. This process is to roughly approximate the scans and not have one upside down or backward. Once that is completed, ITK-SNAP was used to segment the area of the cranial base to be used as a reference for the superimposition using semiautomatic segmentation. The 3D area that was used as the reference is shown in Figure 2. The area of the cranial base to be segmented is manually "painted" using the software, and a range of density is selected according to the patient's bone density, to remove lower density parts such as soft tissues. The software then automatically removes the lower density and the nonpainted areas, leaving only the cranial base.[18] At this point, we have a complete T1 image, a T1 segmented cranial base, a complete T2 image, and a T2 segmented cranial base. The software then combines each image with its respective cranial base (Fig 3).

The registration (superimposition) of the T2 image on top of the T1 image was done on the segmented cranial base, using 3D Slicer, more specifically, the craniomaxillofacial tool, and the setting for nongrowing rigid automatic registration. During the superimposition, T2 is moved and automatically superimposed on a static T1, creating a registered T2 surface model. Video tutorials for cranial base segmentation and the registration process are available online.[19]

Dolphin software was then used to superimpose the pre and post surgical scans of 31 patients. For each patient, T1 and T2 3D images were approximated using 3 landmarks located at the right and left frontozygomatic sutures and the left mental foramen, and superimposed on the cranial base using the voxel-based superimposition tool in the Dolphin 3D software (Fig 4). The area of the cranial base to be used for superimposition is defined by a red box in the 3 slice views (Fig 5). The superimposition was achieved by moving the T2 image on top of the T1 image so that after the superimposition we could create a registered T2 image. The precision of the Dolphin 3D superimposition was then verified using the slice view (sagittal, axial, and coronal views) (Fig 5). After that, the registered T2 scans from Dolphin were exported as DICOM files, and ITK-SNAP software was used to convert the file format to GIPL format. 3D Slicer was then used to segment the whole skull using the Intensity Segmenter tool (the same intensity range was used for all subjects to eliminate any possible error due to the segmentation process) so that a surface model of registered T2 was created for each patient.

Since the registered T2 images from the 2 software packages have the same coordinate system as that of T1, they would line up perfectly if there was no difference in the superimposition technique in both software packages. Quantification of the differences was done by measuring the distance between the 2 surface models, from the 2 methods, using closest-point color maps (Fig 6). Seven areas were selected using the Pick'n Paint tool in 3D Slicer to measure the absolute differences between the 2 models (Fig 7). The 7 areas are nasion, A-point, right zygomatic arch, left zygomatic arch, right gonial angle, B-point, and left gonial angle. Each area has between 150 and 200 points on the surface that are used to calculate the mean difference between the 2 surface areas of the 2 models. After defining these areas with the Pick'n Paint tool, the Mesh Stats tool was used to calculate the absolute differences between the 2 surfaces. The mean absolute distances, standard deviations, and maximum and minimum distances were collected for each of the 7 areas.

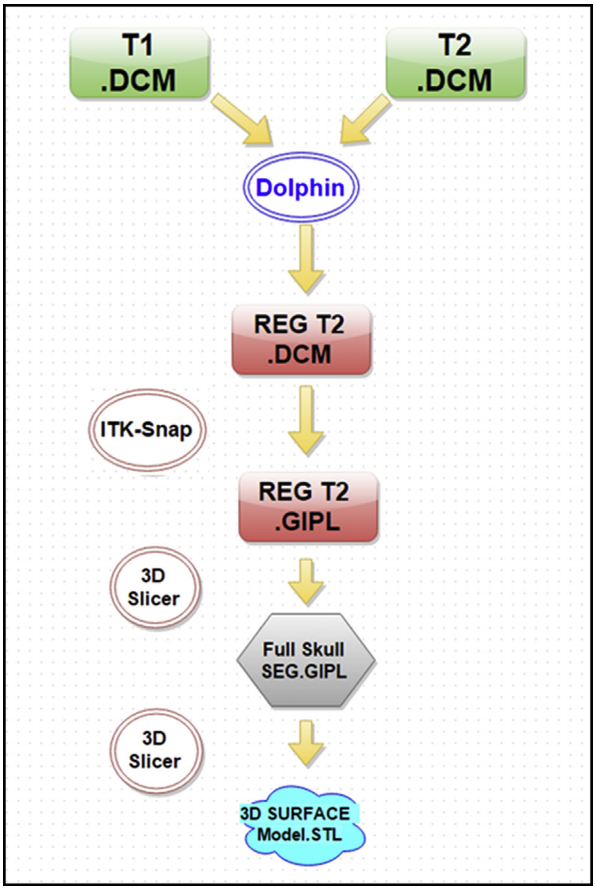

Fig 4. Dolphin 3D method of voxel-based superimposition. The first step is image approximation using landmarks followed by voxel-based superimposition and exporting a registered T2 DICOM (*REG T2*), which is then opened by ITK-SNAP to change the file format, and finally a surface model is created for the comparison.

RESULTS

To test the reliability, the same investigator (M.B.) repeated the superimpositions of 10 subjects after 2 weeks. Intraclass correlation coefficients (ICC) were used to evaluate the reliability. ICC was 0.96, showing great reproducibility (Table I).

Little difference was found when comparing the method of Cevidanes[7,12-14] with the Dolphin method (Table II). The smallest difference was found in the left zygomatic arch region with a mean of 0.09 $\pm$ 0.07 mm, and the largest in the right gonial angle with 0.21 $\pm$ 0.13 mm. All mean differences were less than a voxel size (0.38 mm), and they were considered to have no clinical significance.

DISCUSSION

In this study, we evaluated the precision and reliability of the Dolphin 3D voxel-based superimposition. With the improvements in the image registration algorithm, Dolphin Imaging developed a new tool that is fast (less than 5 minutes), does not require extensive training, uses only 1 software program, and no segmentation is needed before the superimposition. The Dolphin 3D voxel-based superimposition showed no difference when compared with the method of Cevidanes et al,[7,12-14] which has

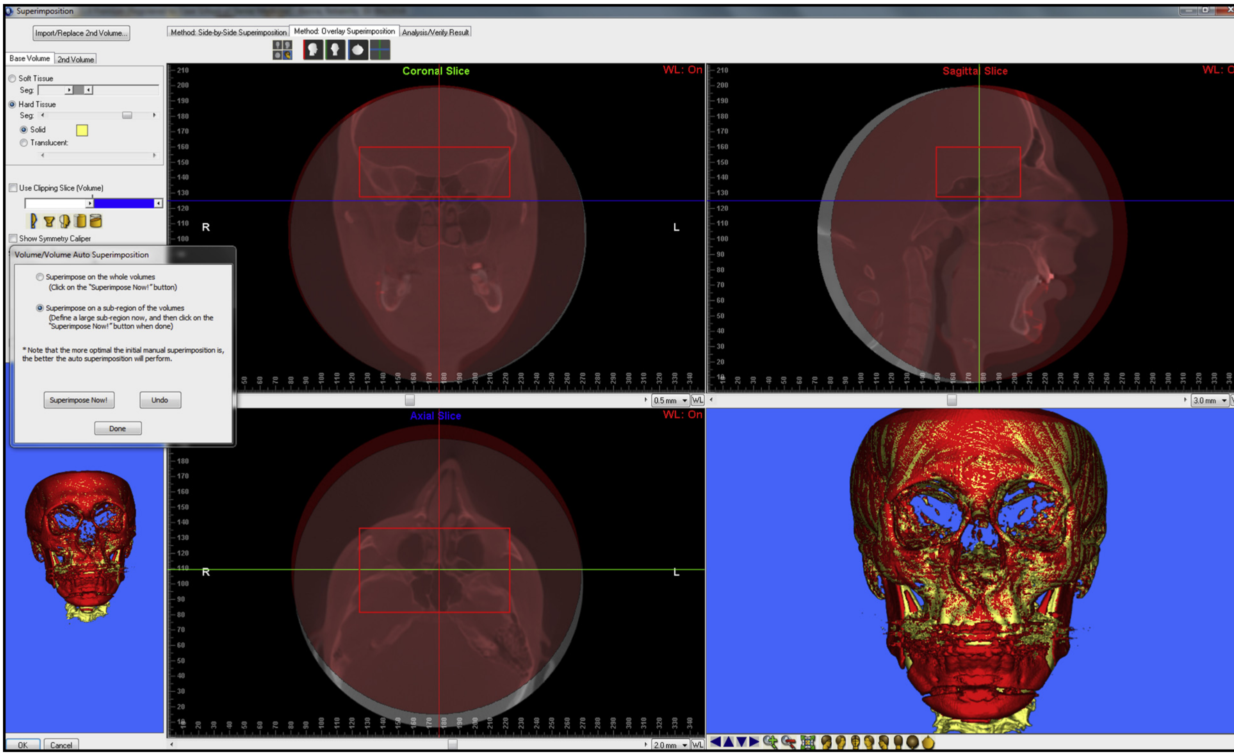

Fig 5. Dolphin 3D voxel-based superimposition on the cranial base. The *red box* is used to define, in 3 dimensions, the area of the cranial base to be used as a reference for the superimposition.

been extensively used, validated, and accepted in the literature. A disadvantage of the Dolphin 3D software is that it is only commercially available, whereas the method of Cevidanes et al uses open-source software programs.

Voxel-based superimposition, even though largely automated, is not too different in its methods from a traditional visual landmark superimposition. In a similar way than when an operator can visually identify landmarks and put them on top of the same landmarks belonging to a posttreatment image for a superimposition, the software can "see" the structures by grayscale differences. The software is able to match similar-looking structures. The images that were used have 4096 gray scale, and the software uses these grayscale values to match the 2 areas of reference. This allows more precise matching. Even though the voxel-based superimposition methods are largely done by algorithms, proper operator management of the images is still crucial for efficient and accurate results. The initial approximation of the images, although a simple step, is important for reducing the working time of the

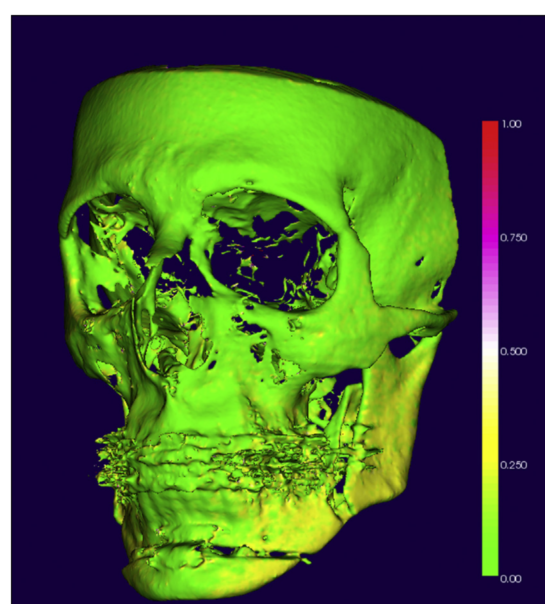

Fig 6. Three-dimensional color map of the registered T2 models from both software programs showing the differences in millimeters.

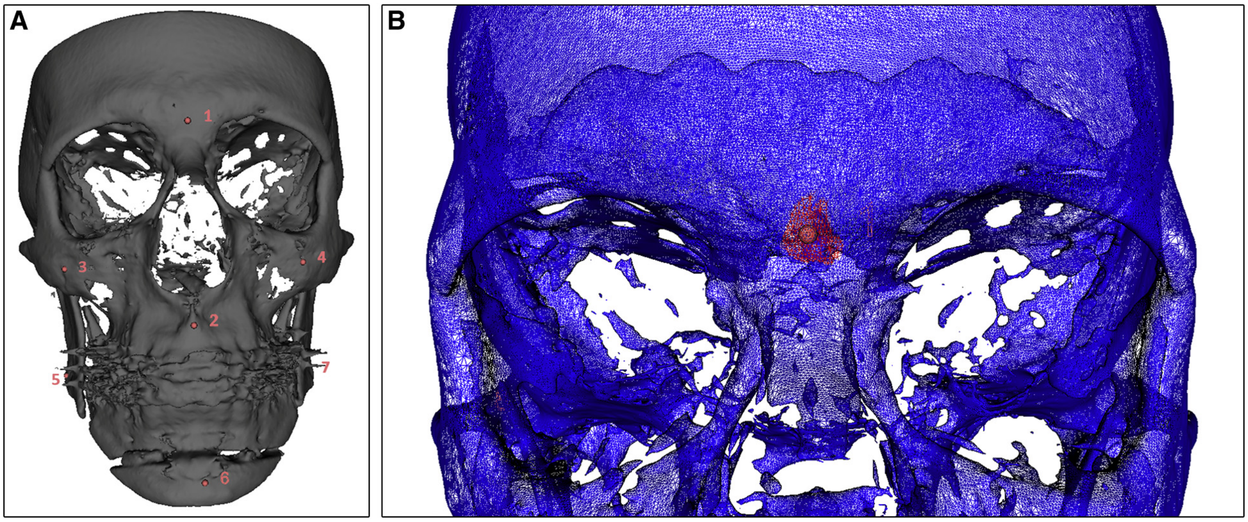

Fig 7. **A,** Fiducial areas were selected using the Pick'n Paint tool in 3D Slicer; **B,** the actual size of fiducial area number 1 in the Pick'n Paint tool.

Table I. ICC values and confidence intervals for repeated measurements of 10 patients

		95% CI	
	ICC	*Lower bound*	*Upper bound*
Average measure	0.964	0.941	0.978

Table II. Differences between the 7 areas using the Mesh Stats tool in 3D Slicer (mm)

	n	*Mean*	*Minimum*	*Maximum*	*Range*	*SD*
Nasion area	31	0.09923	0.024	0.288	0.264	0.072
A-point area	31	0.18813	0.009	0.432	0.432	0.110
Rt zygo area	31	0.11335	0.014	0.329	0.315	0.086
Lt zygo area	31	0.09213	0.011	0.217	0.206	0.057
Rt gonial area	31	0.21042	0.043	0.741	0.698	0.136
B-point area	31	0.18881	0.032	0.410	0.378	0.101
Lt gonial area	31	0.16858	0.068	0.375	0.307	0.082

Rt, Right; *Lt*, left; *zygo*, zygomatic.

program and for the precision of the superimposition. This is true in both methods. Pluim et al[20] found that if the misalignment of the 2 images is large and no approximation is done, the superimposition may fail.

For our results analysis, we used absolute values for the closest point surface distances, since the direction of the difference had no value in our research. This also eliminated the possibility of a positive value counteractimg a negative value.

Since only orthognathic subjects were used for the comparison, there were no expected changes in the cranial base area by growth, but this is not thought to be something that would interfere with the precision of this method. Superimposing 3D images of growing patients may also be done using the gray scale of the cranial base. The same way that an operator can visually see the cranial base anatomy, the software is also able to identify it and use it to match different images. Superimposing growing patients using the Dolphin software in theory will be accurate, but to test such theories could be useful for our literature.

Lee et al[21] used an image-fusion method to superimpose computed tomography images of dry human skulls with different spatial conditions and reported an error of 0.396 mm, which was not affected by positional change. Nada et al[22] tested the reliability of voxel-based superimposition on the anterior cranial base and zygomatic arch using Maxilim software and reported small average errors. Weissheimer et al[23] recently evaluated a fast method of 3D voxel-based superimposition using OnDemand 3D software and concluded that the mean superimposition errors were less than 0.5 mm in growing and nongrowing patients. In this study, Dolphin 3D showed a maximum mean difference of 0.21 mm, which is clinically insignificant.

The voxel-based superimposition method allows a superimposition on the cranial base using approximately 300,000 voxels and accurately matches structures using high grayscale levels.[7] This method has the potential to be more reproducible and precise than the traditional 2D superimpositions. Voxel-based regional superimpositions, such as maxillary or mandibular superimposition, should also be possible when using proper registration structures.

CONCLUSIONS

Dolphin 3D voxel-based superimposition, a fast and user-friendly method, is precise and reliable.

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