Superimposition of 3D cone-beam CT models in orthognathic surgery

Alexandre Trindade Simões da Motta*, Felipe de Assis Ribeiro Carvalho**, Ana Emília Figueiredo Oliveira***, Lúcia Helena Soares Cevidanes****, Marco Antonio de Oliveira Almeida*****

Abstract

Introduction: Limitations of 2D quantitative and qualitative evaluation of surgical displacements can be overcome by CBCT and three-dimensional imaging tools. **Objectives:** The method described in this study allows the assessment of changes in the condyles, rami, chin, maxilla and dentition by the comparison of CBCT scans before and after orthognathic surgery. **Methods:** 3D models are built and superimposed through a fully automated voxel-wise method using the pre-surgery cranial base as reference. It identifies and compares the grayscale of both three-dimensional structures, avoiding observer landmark identification. The distances between the anatomical surfaces pre and post-surgery are then computed for each pair of models in the same subject. The evaluation of displacement directions is visually done through color maps and semi-transparencies of the superimposed models. **Conclusions:** It can be concluded that this method, which uses free softwares and is mostly automated, shows advantages in the long-term evaluation of orthognathic patients when compared to conventional 2D methods. Accurate measurements can be acquired by images in real size and without anatomical superimpositions, and great 3D information is provided to clinicians and researchers.

Keywords: Cone Beam Computed Tomography. 3D image. Computer-assisted surgery. Computer simulation. Orthodontics. Oral surgery.

* Professor, Department of Orthodontics, Fluminense Federal University, Niterói, Brazil.
** PhD student, Department of Orthodontics, State University of Rio de Janeiro, Brazil.
*** Professor, Department of Oral and Maxillofacial Radiology, Maranhão Federal University, São Luís, Brazil.
**** Assistant Professor, Department of Orthodontics, University of North Carolina at Chapel Hill.
***** Professor and Chair, Department of Orthodontics, State University of Rio de Janeiro, Brazil.

INTRODUCTION

The evaluation of the craniofacial complex in Orthodontics and Orthognathic Surgery usually involves a clinical exam together with diagnostic tools like photographs, dental casts and radiographs. Traditional radiographic methods have some diagnostic limitations, such as magnification, superposition and other distortions related to bidimensional (2D) representation of tridimensional (3D) structures.[17]

Aiming to overcome such limitations, spiral computed tomography was introduced in dental specialties, for example, osseointegrated implant surgical planning and oral pathology diagnosis.[17,27] Three-dimensional radiographic diagnosis has been intensified in Dentistry through cone-beam computed tomography (CBCT), a method avoiding some drawbacks of 2D methods. Its use has increased all over the world, specifically in Orthodontics, since the first paper was published[21] in 1998, and since the first machine was introduced in the U.S. in 2001.[17]

CBCT has been described[5,16,21] as the 3D method of choice for maxillofacial imaging due to some advantages over "medical" tomography, like the following: Less expensive machine and scan, lower radiation dose and faster acquisition time, good contrast for facial bones and teeth, and the possibility of obtaining all set of conventional orthodontic images in just one exam. This method allows the generation of 3D reconstructions with a complete visualization and measuring of facial structures.[3]

Novel orthodontic applications of advanced 3D imaging techniques include virtual models' superimposition for the assessment of growth, changes with treatment and stability, 3D soft-tissue analysis and computer simulation of surgical osteotomies. Quantitative and qualitative analysis of skeletal displacement, adaptive response and resorption that could not be attempted with 2D techniques can now be accomplished through 3D CBCT reconstructions and superimpositions.[3,5,19]

The purpose of this paper was to describe a methodology for superimposition of 3D virtual models, reconstructed from computed tomography of the face, indicating tools for quantitative and qualitative analysis and presenting visualization possibilities in ortho-surgery patients.

STABILITY OF ORTHOGNATHIC SURGERY

The hierarchy of stability for different orthognathic procedures shows that mandibular advancement up to 10mm is highly stable in patients with short or normal face, as well as maxillary impaction, when compared to other surgical treatments. Both are defined as having more than a 90% chance of presenting less than 2 mm change at landmarks and almost no chance of more than 4 mm change during the first post-surgical year. Surgical repositioning of the chin via lower border osteotomy, the most prevalent adjunctive procedure, also is highly stable and predictable.[1,25,26]

Advancement of the maxilla is described as stable in the forward movement of moderate distances (up to 8 mm), showing an 80% chance of less than 2 mm change, a 20% chance of 2-4 mm relapse, and almost no chance of more than 4 mm change. The maxillary component of vertical asymmetry surgery also can be judged to be stable, which usually involves moving one side up and perhaps the other side down to correct a canted occlusal plane. Some procedures are considered stable if rigid internal fixation (RIF) is used: the combination of maxillary impaction and mandibular advancement (Class II) or set-back (Class III), maxilla forward plus mandible back, and mandibular asymmetric correction, even though the data are more limited for the last.[1,25,26]

Three procedures are in the problematic category, defined as a 40-50% chance of 2-4 mm post-surgical change and a significant chance of more than 4 mm change: mandibular set-back, downward movement of the maxilla, and maxillary expansion. Even with these procedures, at least half of the patients experience essentially no post-surgical change.[1,25,26]

Rotation and transverse condylar displacements followed by resorption and remodeling as a consequence of mandibular surgical advancement have been described,[2] but there is still not enough evidence to ascertain if this would interfere on post-treatment stability. Previous studies[12,13] used tomographic images to assess post-surgery condylar position and displacements, but not condylar remodeling.

Skeletal remodeling in the condyles is considered an important factor on post-surgery stability, and might influence treatment outcomes. It is required that the clinician find several anatomic landmarks in the determination of condylar morphological changes and its influence over post-operative stability. In conventional cephalometrics, problems during landmark identification have been considered a significant source of error in important craniofacial measurements.[9]

Long term condylar resorption with sagittal relapse and anterior bite opening were described as potential clinical problems following mandibular advancement,[9] occurring in 5-10% of these patients, but a long-term increase in mandibular length (ie, growth at the condyles) is as likely as a decrease because of resorption.[18,28]

A great impact of 3D imaging over clinical practice is expected, especially in three fields: surface mapping of facial soft-tissue, digital modeling of the dental arches, and visualization and measuring of skeletal structures. The development of CBCT[21] low-dose high-resolution maxillofacial images will allow an accurate assessment of jaws dimension and condylar morphology.

3D MODEL SUPERIMPOSITION

The complex movements during surgery for dentofacial deformities clearly need to be assessed in three dimensions to improve outcome, stability and reduce symptoms of temporomandibular joint disorder after surgery.[4]

Tomographic image reconstruction techniques have been used in diagnosis, treatment planning and surgical simulation.[11,13,23,29] Otherwise, registration/superimposition of three-dimensional images poses operational challenges, mostly because of the difficult establishment of anatomic landmarks on actual surfaces without standards for three-plane spatial localization.[4]

A study[3] validated the method of construction, superimposition and measuring of surface distances between 3D CBCT model surfaces, adapting softwares and imaging analysis from magnetic resonance neurologic studies. The position of the condyles and rami posterior borders were compared in ten patients treated by means of maxillary surgery only, between one week before surgery and one week after surgery. Mean differences between surfaces showed a precision (0.70 to 0.78 mm) very close to tomography spatial resolution (0.6 mm), with interobserver non-significant differences (mean = 0.02 mm).

Changes in the condyles and rami after maxillary advancement and mandibular set-back (11 Class III patients) and maxillary surgery only (10 patients with various malocclusions) were compared through the superimposition of 3D CBCT models. Condylar displacements were small in both groups (means = 0.77 and 0.70 mm, respectively), without significant changes. Rami displacements were greater in the first group (two-jaw surgery), with a mean posterior rotation of 1.98 mm and 8 patients showing maximum surface distances ≥2 mm, whereas the second group showed significant smaller displacements (0.78 mm), with only one individual showing distances ≥2 mm. This method clearly showed the localization, magnitude and direction of mandibular structural displacements, as well as allowed the quantification of vertical, transverse and anteroposterior movements of the ramus that accompanied mandibular surgery, but not maxillary surgery.[4]

Follow-up of the same sample showed important preliminary data. The mean displacement/remodeling in the condyles one year after surgery was 1.07 and 0.77 mm for the 2-jaw group and the maxillary surgery group, respectively ($p < 0.05$). All patients from the first group presented remodeling and movement with anterior rotation in the rami (mean = 1.85 mm), whereas in the second group the mean displacements in the rami were 0.86 mm ($p < 0.01$). The data suggested that maxillary position remained quite stable and that combined surgery resulted in greater positional changes and remodeling in the condyles and rami than maxillary surgery only.

Another study[8] also compared maxillary advancement and mandibular set-back (16 Class III patients) versus maxillary surgery only (17 Class III patients) groups. Both showed a rami posterior-inferior displacement tendency with surgery (T2 = one week after surgery), but an anterior-superior movement after splint removal (T3 = six weeks after surgery). The first group presented displacements in the posterior border of the rami >4 mm in 44% and between 2-4 mm in 22% of the patients after surgery. Between T2-T3, the rami presented displacements <2 mm in 97% of the cases. The maxilla only group did not present displacements >4 mm in T2. The rami moved <2 mm in 76% and 85% of the cases between T1-T2 and T2-T3, respectively (T1 = pre-surgery). Condyle displacements in the combined surgery group showed a posterior tendency between T1-T2 (72% of the patients) and a superior tendency between T2-T3 (75%). Results were similar for the second group, posterior (71% of the patients) between T1-T2 and superior (74%) between T2-T3. Condyle displacements were <2 mm in 91% of the cases between T1-T2 and T2-T3 in the maxilla group, and <2 mm in 93% (T1-T2) and 100% (T2-T3) in the combined group. The 2-jaw surgery resulted in greater displacements in the short-term, but condylar displacements were small in both groups.

A study[10] assessed maxillary changes in Class III patients who underwent Le Fort I osteotomy. Using 3D-model superimpositions between pre-surgery, one week post-surgery and one year post-surgery, no significant difference was found in the position of the maxilla on the anteroposterior or transverse planes, concluding that this kind of procedure was stable in the first year of observation.

Aiming to identify complex skeletal asymmetry in patients with hemifacial microsomia, a study compared the anatomic and positional differences of condyles, rami and mandibular bodies surfaces between the left and right side. A median plane was built in the 3D CBCT models and a mirroring technique was used to superimpose the cranial bases and compare both sides, displaying variable locations with asymmetry. It was concluded that this method and the preliminary findings could enhance the quantification and localization of the asymmetry for a more precise surgical planning, since such information could not be obtained from 2D methods. Therefore, this novel diagnostic tool can reduce the need of exploratory surgery.[7]

Rami and condyles positioning and remodeling after Class III surgical treatment in 19 patients, 11 with combined maxillary advancement and mandibular set-back and 8 with maxillary advancement only, were compared through the superimposition of 3D CBCT models. It was verified that the combined surgery generated greater structural positional and remodeling changes than the maxilla only surgery. Furthermore, the posterior displacement of the ramus was present even one year after surgery, while in the maxilla only group an anterior movement was observed in the same period.[15]

Changes in the condyles, rami and chin were evaluated with 3D superimposition in 20 retrognathic patients with normal or horizontal facial pattern treated by means of mandibular advancement. Pre-surgery, 1-week and 6-week post-surgery scans were compared, the last taken immediately after splint removal. Important structural displacements were observed in the condyles and rami with surgery in all the cases, as well as the expected chin advancement with a vertical increase of the lower third of the face in brachycephalic patients. Despite the great individual variability, an overall physiologic short-term adaptive tendency was observed toward the pre-surgical position of the condyles and rami. Additionally, the anterior or anterior-inferior displacement of the chin remained stable in 75% of the patients, while 25% presented some posterior displacement tendency of small magnitude. With long-term one-year and two-year follow-up, this sample's model superimpositions will be able to show important information on mandibular correction stability.[19,20]

Surgical displacements and adaptive responses occur relative to adjacent structures in the craniofacial complex. For this reason, the measurements from 3D curves and surfaces are not isolated measurements but are determined by the manner of assembly of different parts of the craniofacial complex. The mandibular rotations after surgery might be influenced by maxillary, mandibular, and articular fossae morphology, positioning and interrelationships, and type of maxillary surgical movement.[14] Stability studies showed that maxillary displacement forward or upward is more stable than maxillary displacement downward.[1,24] Maxillary displacement downward during 2-jaw surgery would certainly influence mandibular position. The association between maxillary surgeries and the type of mandibular rotation requires further investigation and future long-term follow-up studies of condylar and rami remodeling.[4]

METHODOLOGY FOR AUTOMATED SUPERIMPOSITION

Tomographic exams must be taken in different time-points (pre-surgery, immediate post-surgery, long-term follow-up). The imaging protocol may vary depending on the machine, and for the development of this methodology involved a 30-second head CBCT scanning acquired in centric occlusion with a field of view of 230 x 230 mm using the NewTom 3G (Aperio Services LLC, Sarasota, FL, 34236). A primary reconstruction of the tomographic slices was done by the radiology technician immediately after the scan, with a 0.3 x 0.3 x 0.3 mm voxel resolution. Differently from 2D procedures, since the whole 3D volume of the craniofacial complex is captured during this exam, tomographic slices can be acquired with less concern to head positioning standards.

Imaging tomography files are then exported in DICOM format (Digital Imaging and Communication in Medicine), the universal format for medical and dental tomographic diagnosis imaging. Using the Imsel software, the files are converted to GIPL format, which is read by open access softwares (http://www.ia.unc.edu/dev/download/index.htm), as the following. Each file is reformatted through the Imagine software to 0.5 x 0.5 x 0.5 mm voxels, reducing file size by half, thus requiring less computing capacity and consuming less time of work during different phases of the methodology.

Segmentation represents the volumetric reconstruction of the visible anatomic structures in the tomographic slices. The InsightSNAP software was used for this procedure, also allowing navigation through the slices in the axial, sagittal and coronal planes. From a set of more than 300 axial, lateral and anteroposterior cross-sectional slices for each image acquisition, 3D models of the cranial base, maxilla and mandible were constructed (Figure 1).

In the vertical plane, segmentation of the cranial base is done including from the inferior anatomic limit (Basion) to the superior limit of the tomographic image. The whole skeletal contour is included in the transverse and AP planes. The green color is used as a standard for the cranial base, while other structures are segmented in the red color. Different colors allow the division of structures for superimposition procedures and quantification of displacements.

Dolphin Imaging 3D (Dolphin Imaging & Management Solutions, Chatsworth, California) and InVivo (Anatomage, San Jose, California, USA) commercial softwares display a 3D rendering rapid reconstruction, an image projection that allows only visualization of 3D structures, whereas the volumetric reconstruction used in the present method allows actual measurements of structural changes and surface displacements.[6,22]

To evaluate within-subject changes, images of different phases were superimposed with the software Imagine in a fully automated method using voxel-wise registration to avoid observer-dependent location of points identified from overlap of anatomic landmarks. Since the cranial base is not altered by the surgery, its surfaces were used in the registration procedure, where the software compares the grey level intensity of each voxel between two CT images. In this way, the cranial base of the presurgery CT is used as reference for the other time-points (Figure 2).

In the next step, to control the cropping for a quantitative analysis of regions of interest, the 3D models at various time-points were combined with the Imagine tool (Figure 3). Aiming to reduce image disc space, 3D display of the cranial base was discarded at this point, showing only the maxilla and mandible.

In the combined models, anatomic regions of interest could be simultaneously selected in different colors using the InsightSNAP software (Figure 4). Anatomic references are used to determine the cutting of regions: (1) the chin anatomic region is defined by the long axis of the lower canines post-surgery; (2) the posterior border region is defined by a plane tangent to the anterior contour of the condyles and parallel to the posterior border of the rami; e (3) the inferior limit of the condylar region is defined by the interface of the posterior border cut. Since the combined 3D models are simultaneously cutted, precision of this selection is controlled. The voxels at the chin are painted in blue, the rami in green, and the condyles in yellow.

The combined cutted structures were then divided with the software Imagine, keeping their spatial positioning in the tomography (Figure 5). Each region of interest was then an-

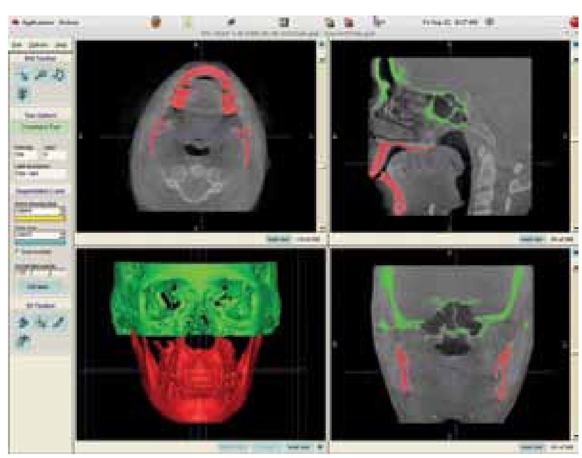

FIGURE 1 - Segmentation of the three-dimensional model, including the cranial base (green) and the maxillo-mandibular complex (red). Segmented areas can be viewed in the slices and in the 3D model.

alyzed separately with MeshValmet software, where measurements of the surface distances between two different time-points within the same subject allowed the quantification of rami, condyles and chin displacements that accompanied mandibular surgery.

After all the structures are segmented, registered, combined and separated into time-points, two additional file formats are required for visualization and quantification of surgical changes. The GIPL files of the maxillo-mandibular complex as well as the separate anatomic regions are converted into .IV and .META files through the Vol2Surf software, turning all the volumes into surfaces. The first format is compatible with the software MeshValmet, where quantitative and qualitative analysis are done (color coded maps), while the second format is compatible with the FltkSOV3Dtool, where qualitative analysis is done through the semi-transparencies method. Three-dimensional graphical rendering of the volumetric object then allows navigation between voxels in the volumetric image and the 3D graphics with zooming, rotating and panning.

MeshValmet automatically computes the distances between two time-points and in the same patient, allowing the quantification of the displacements following mandibular (rami, codyles and chin), maxillary or two-jaw surgery (Figure 6).

The resulting 3D graphic display of the superimposed structures is color-coded with the regional magnitude of the displacement

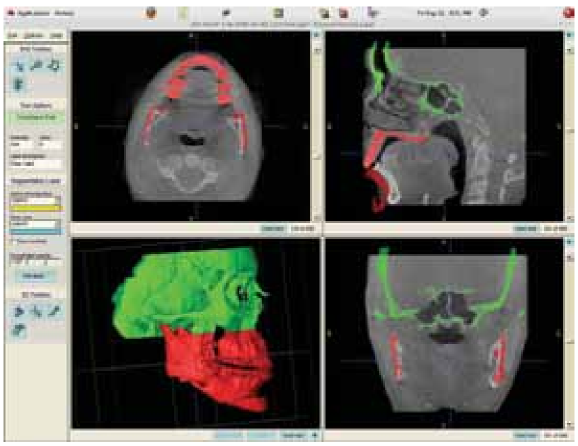

FIGURE 2 - After the registration procedure with the Imagine software, the superimposition between the post-surgery 3D model (color) and gray scale pre-surgery image can be observed, showing matching cranial bases and displaced mandibular structures (mandibular advancement and genioplasty). A correct superimposition between models of the two phases is then confirmed.

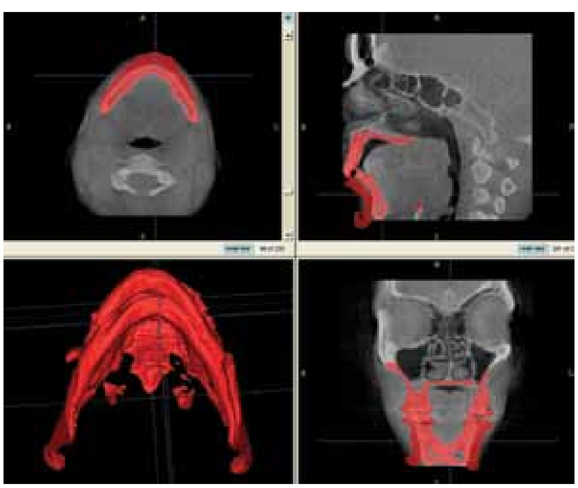

FIGURE 3 - Combination between pre-surgery, 1-week, 6-week and 1-year post-surgery follow-up models. The mandibular advancement between pre-surgery and post-surgery models can be observed in the slices and in the 3D view.

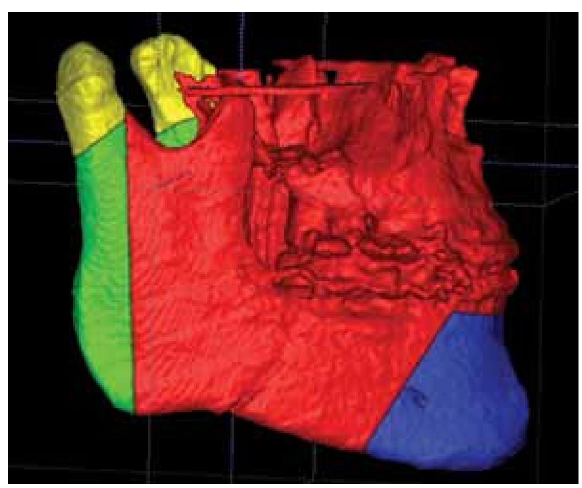

FIGURE 4 - Selection of the anatomic regions of interest in the combined model, allowing quantitative and qualitative analysis of the surgical displacements.

between two segmentations. Objects are compared according to a sequence (B→A), exhibiting the anatomy or external contour of the second time-point as a reference, with colors displaying the difference between them. Surfaces in red mean an outward displacement and have positive values in the histogram listing of the surface distances. Surfaces in blue indicate inward displacements and have negative values. The absence of surgical displacement is indicated by the green color code. The intensity of the color is associated to the magnitude of the displacement (Figure 7).

Another tool (FltkSOV3Dtool) allows the visualization of the different degrees of transparencies, assessing the boundaries of the mandibular rami, condyles and chin between superimposed models of two different time-points. The visualization of the superimpositions clearly identifies the location, magnitude and direction of mandibular displacements. This method seems to be easily assimilated by the clinician, but only provides a qualitative analysis, without numerical data.

For a better understanding of the surgical changes, both the whole maxillo-mandibular complex (Figure 8) and the isolated specific regions (Figure 9) are used. Figures 10, 11 and 12 show the 3D superimposition of patients treated by means of mandibular advancement to correct retrognathism, highlighting important skeletal findings through this method.

Despite soft-tissue visualization is better performed with magnetic resonance imaging and a better contrast between soft and hard-tissues is observed with spiral computed tomograhy, 3D models of the soft-tissue of the face can be precisely reconstructed with lower cost and radiation and still provide important information of facial esthetic response to surgical movements.[19] Figures 13, 14 and 15 exhibit segmentations and superimpositions through the methods of semi-transparencies and color coded maps of a Class III patient treated by means of maxillary advancement and mandibular set-back. Some imperfections can be noted in the images, resulting from factors like: image cutting in size (machine small field of view), low contrast for cartilage (ears), head movement during acquisition, facial swelling in acquisition only one week after surgical procedure, bracket metallic artifacts, and cervical artifacts due to patient head lying down on a pillow during NewTom 3G scan.

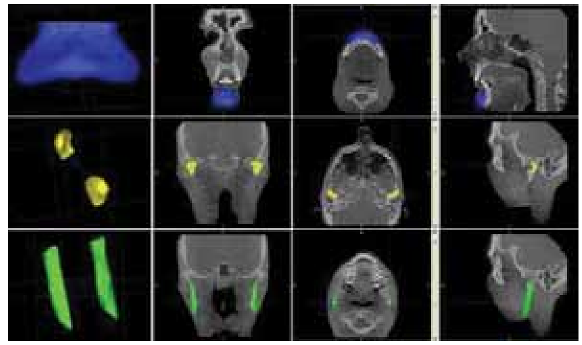

FIGURE 5 - From left to right, visualization of the 3D models, coronal, axial and sagittal slices after division of the anatomic regions of interest.

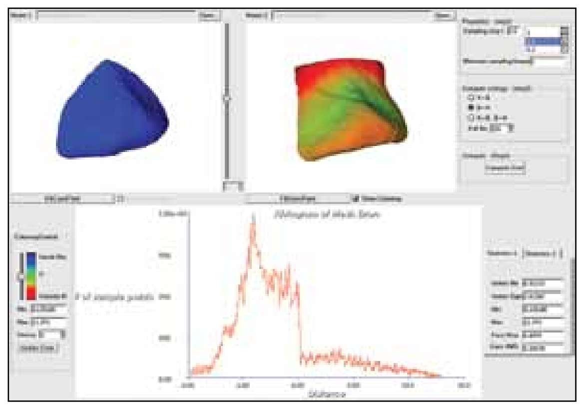

FIGURE 6 - Example of the MeshValmet software screen during the measurement of a chin displacement between pre and post-surgery, showing the surface distances (histogram values) and the direction of displacement (image on the right). It is important to highlight that, on the superimposed 3D model (right) the anatomy or external contour of the post-surgery model is observed, and the color map shows the displacement behavior.

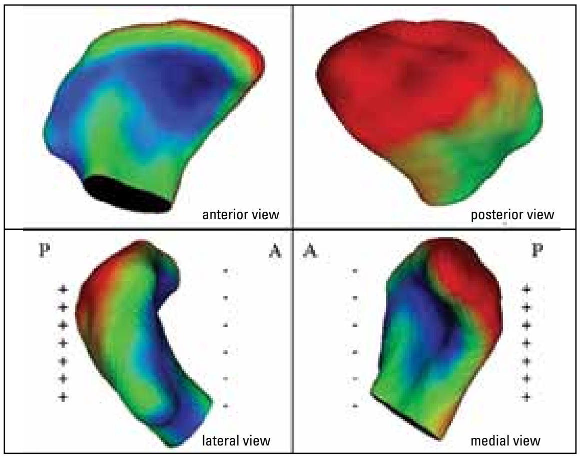

FIGURE 7 - Visualization of a right condyle displacement through color coded maps. Red surfaces indicate a posterior-superior-medial (outward) displacement between pre-surgery and post-surgery, opposed by blue surfaces (inward) (A = anterior; P = posterior).

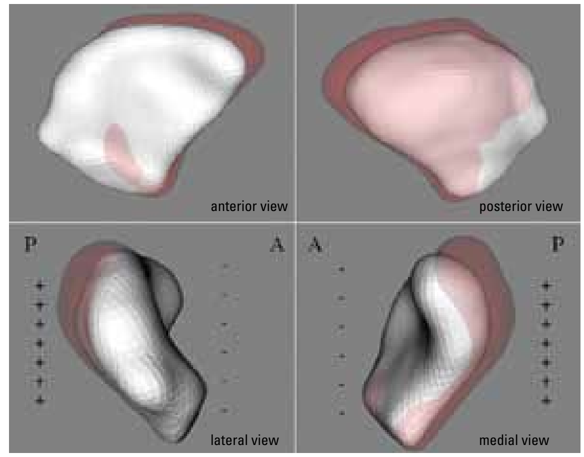

FIGURE 8 - Visualization of the same condyle shown in Figure 7 through semi-transparencies in the FltkSOV3Dtool software (Pre-surgery in solid white and post-surgery in transparent red).

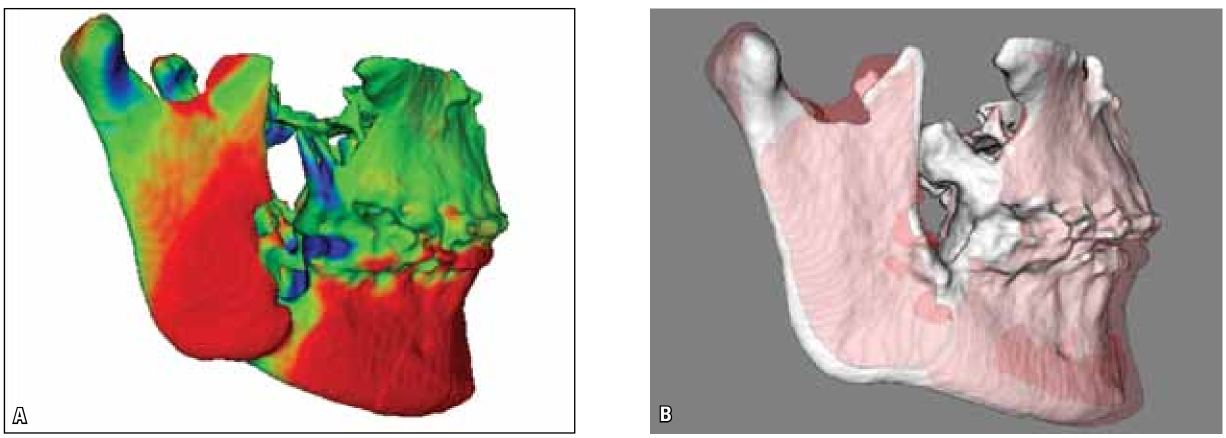

FIGURE 9 - Color maps (**A**) and semi-transparencies (**B**) of the maxilla and mandible in a superimposition between pre and post-surgery phases. An overview of the surgical changes facilitate the observation of regional displacements in the condyles, rami and chin. **A**) Mandibular body and chin advancement shown in red (outward movement), as well as torque in the right ramus (lateral movement of the ramus in red and medial movement of condylar neck in blue). **B**) Superimposition between pre-surgery (solid white) and the 1-week after surgery model (transparent red) exhibiting displacements of the chin, mandibular body, ramus and condyle in a lateral view.

DISCUSSION

Computed tomography has been used for many years to assess complex skeletal discrepancies and surgical cases,[13,23,29] but there are many challenges on its clinical application. The present methodology represents an alternative to some of these challenges, using: (1) relatively low radiation doses, inherent to CBCT and comparable to a complete periapical exam;[16] (2) advanced image analysis methods, calculating distances between anatomic surfaces on the measurement of changes with treatment, not depending on the localization of 3D anatomic landmarks which can be a relevant source of error;[3,4] (3) public softwares developed for research purposes, and (4) surface models instead of 3D rendering, allowing volumetric measuring of structural changes.

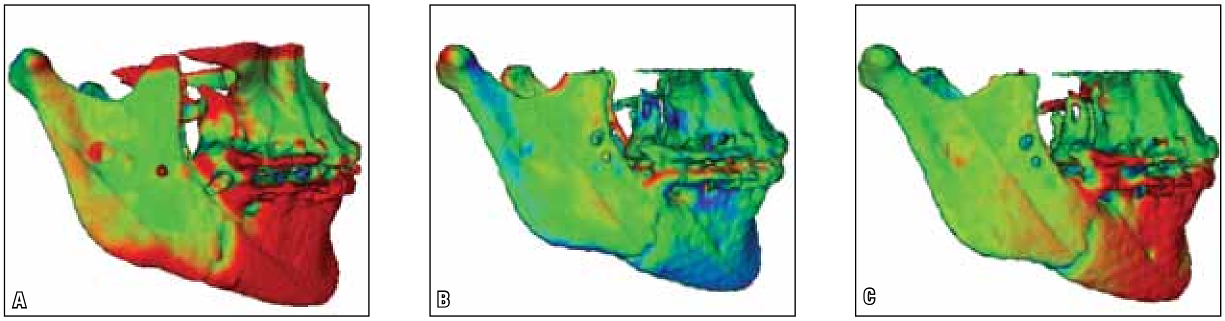

FIGURE 10 - Superimpositions between pre-surgery to immediately post-surgery with splint in place (**A**), immediately post-surgery to splint removal (**B**), and pre-surgery to splint removal (**C**) of a mandibular advancement case. Some posterior (inward) movement of the chin is noted in **B**, shown by the blue color code. It can also be noted by the comparison between different area and density of red surfaces representing the anterior (outward) displacement in **A** and **C**. Still, the resultant superimposition in **C** shows an acceptable maxillo-mandibular relation at splint removal, considered a short-term stability. The right ramus shows a slight lateral movement in **A** (outward), a recovery tendency in **B** (inward), and green surfaces in **C** confirming the adaptive response.

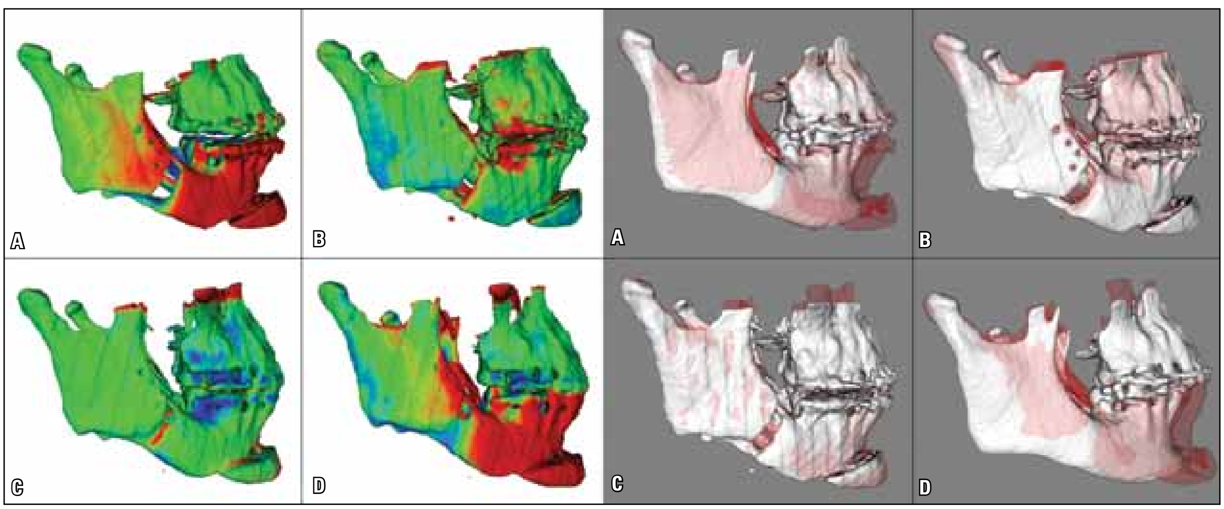

FIGURE 11 - Example of a mandible and chin advancement with excellent stability. **A**) pre-surgery X 1-week post-surgery; **B**) 1-week post-surgery X 6-week post-surgery; **C**) 6-week post-surgery X 1-year post-surgery; **D**) pre-surgery X 1-year post-surgery. Comparison using color maps (left) and semi-transparencies (right) between **A** (T1 in white and T2 in red) and **D** (T1 in white and T4 in red) shows that small condylar and rami displacements occurred with surgery, but surgical results were maintained at the 1-year follow-up. Superimpositions **B** (T2 in white and T3 in red) and **C** (T3 in white and T4 in red) show slight changes between phases on the anterior region, and some posterior movement only in **B**. Besides the absence of significant vertical change on this case, the genioplasty is known to be a highly stable adjunctive procedure.

The automated superimposition method[3,4] represents an innovation if compared to manual methods,[13] since the first is based on a fully automated voxel-wise registration to avoid observer-dependent location of points identified from overlap of anatomic landmarks, while the second depends on the operator to superimpose and turn the post-surgery tomography until reference landmarks match the correspondent pre-surgery landmarks. Besides, differing from adult patients, the described method allows the superimposition on the anterior cranial fossa surfaces of growing children, describing growth relative to the individual cranial base.[5]

Compilation and adaptation of softwares for model construction and evaluation of changes with treatment through time is one of the greatest challenges of 3D imaging.

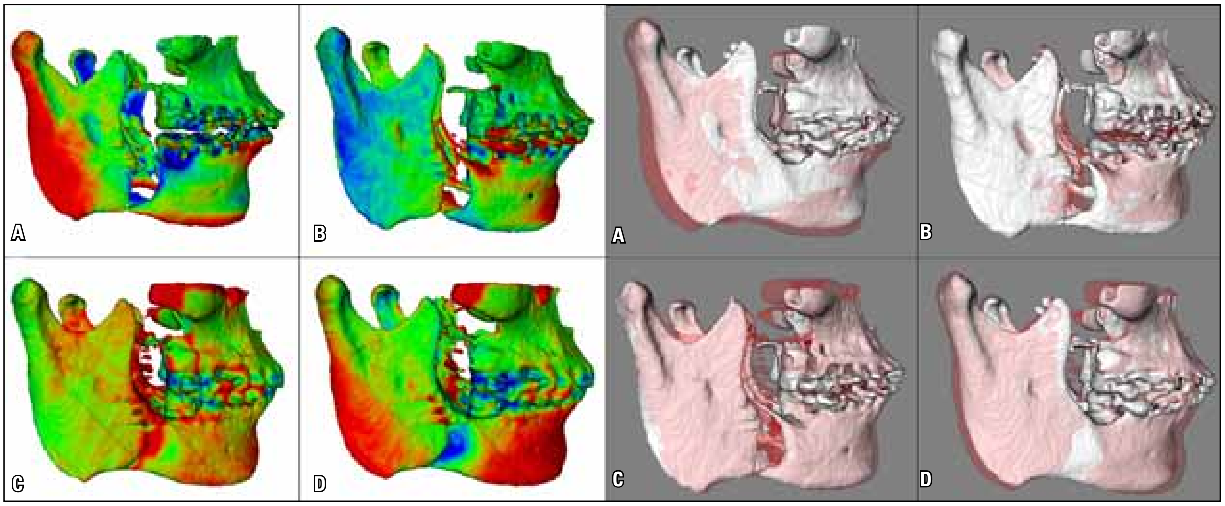

FIGURE 12 - Example of a mandibular advancement case showing superimpositions with color maps (left) and semi-transparencies (right). **A**: pre-surgery x 1-week post-surgery; **B**: 1-week post-surgery x 6-week post-surgery; **C**: 6-week post-surgery x 1-year post-surgery; **D**: pre-surgery x 1-year post-surgery. Superimposition **A** shows that the patient presented more vertical than horizontal changes with surgery, since there was a small overjet but deep overbite, and improvement of the lower facial height was planned. A remarkable posterior displacement of the rami and the chin with surgery is also noted in superimposition **A**, resulting in a remarkable anterior movement after splint removal (**B**), shown as red on the chin and as blue on the ramus. Superimposition **C** shows small changes between 6-week post-surgery and 1-year post-surgery, even though suggests a mandibular displacement on the chin, possibly related to bone remodeling and/or resorption. Superimposition **D** highlights anterior and inferior displacements on the chin, and posterior movement of the rami and condyles that remained displaced.

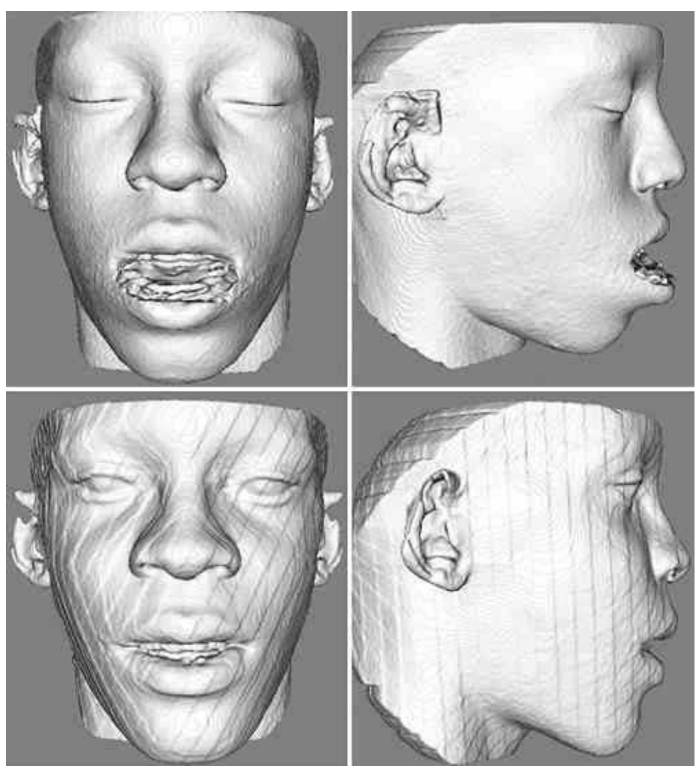

FIGURE 13 - 3D Models including the soft-tissues of a Class III patient with mandibular prognathism, midlle third hypoplasia, and labial incompetence with a hypotonic and everted lower lip (top). Soft-tissue changes six weeks after maxillary advancement and mandibular set-back are shown in the bottom row.

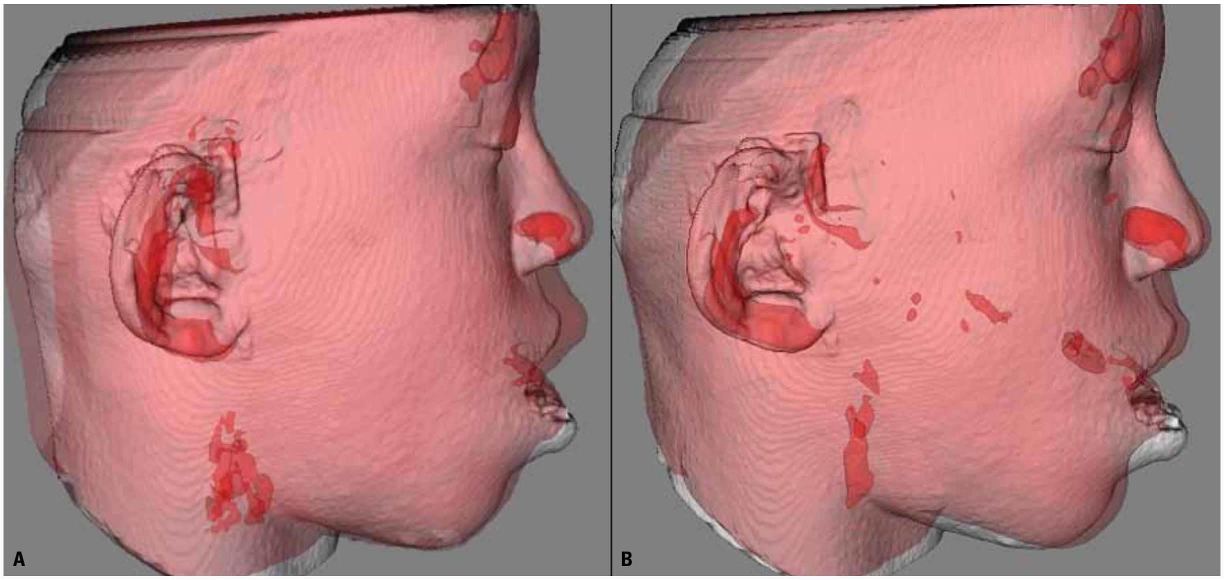

FIGURE 14 - Semi-transparencies displaying soft-tissue changes between pre-surgery (solid white) and 1-week post-surgery (transparent red) on the left, and between pre-surgery (solid white) and 6-week post-surgery (transparent red) on the right. Note important facial changes resulting from skeletal displacements (post-surgical swelling on **A**), for example, nasal and upper lip projection after maxillary advancement, and lower lip postural and soft-tissue chin improvement following mandibular set-back.

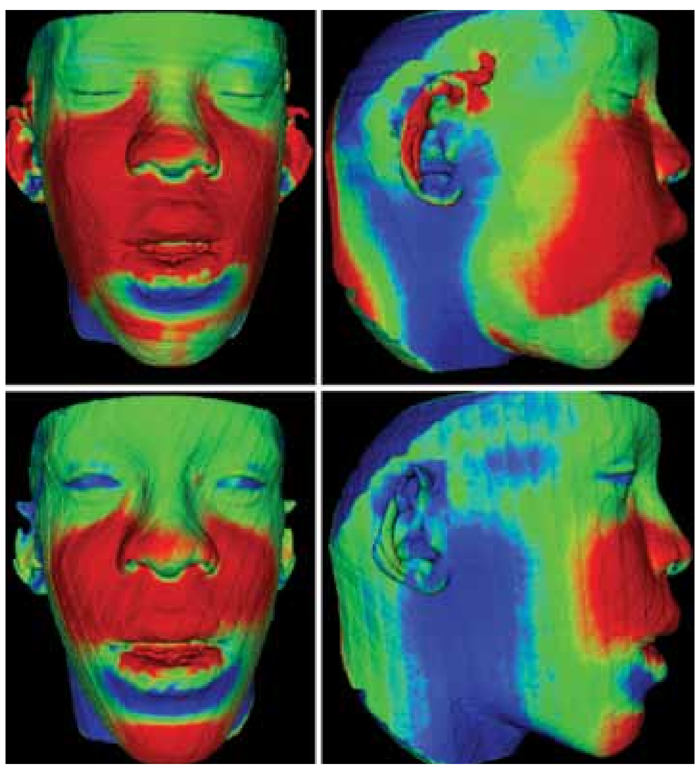

FIGURE 15 - Surface distance color maps between pre and post-surgery models are shown in the top row and between pre and 6 weeks post-surgery in the bottom row. Surface of cranial base was used for registration. Note that the maxillary advancement is shown in red and the mandibular set-back in blue. The color maps in the top row show the post-surgical swelling. Frontal views show important changes in the midlle third of the face, for example, AP improvement and nasal base enlargement. The cervical area shows artifacts of change in position of the head in different CBCT acquisitions as these models were built from NewTom 3G images that were acquired with the patient head lying down on a pillow.

Commercial softwares allow a 3D rendering from tomographic slices, very useful for a clinical observation of craniofacial bones.[6,22] Otherwise, this kind of three-dimensional reconstruction is good for visualization purpose only. The described superimposition requires the segmentation of a real surface model, with internal volume and 3D surfaces that can be compared in different time-points. The visualization of superimposed models and the calculated surface distances clearly exhibit the localization, magnitude and direction of the mandibular rotations with surgery, allowing quantification of AP, transverse and vertical movements of the anatomic regions involved in orthognathic surgery.[3,19]

Besides its research validity, this method seems to have great clinical advantages for individual analysis in routine ortho-surgical cases or in the most complex cases, and is a promising method for Orthodontic and Maxillofacial Surgery education. Limitations for Brazilian reality still are the CBCT machine cost and technically the time and expertise needed for working with 3D models. The generation, superimposition and surface comparison of three-dimensional images demand operational time, computer hardware built for image manipulation, great archiving capacity and the use of various softwares. All the softwares described are freely available and most of them are constantly updated. There is a trend for compilation of different functions performed by different tools in only one complete, intuitive, user-friendly and less time-consuming software.

Novel methods for planning and monitoring the surgical procedure using 3D computerized imaging, from a registration between the patient and his respective 3D CBCT model based in metallic markers in the surgical splint, may represent an advance to controlling the factors influencing the displacement and repositioning of structures in orthognathic surgery. Maxillary movements can be monitored in real time, verifying, for example, the amount of impaction and advancement on the computer screen during surgery, with the advantage of having structural rigid references like the cranial base.[8]

The application of 3D superimposition is not limited to surgical treatment, because using the cranial base as reference, changes with treatment or orthodontic-orthopedic treatment can also be assessed. Novel applications of this method assesses soft-tissue changes with treatment, changes in arch size and form with orthodontic mechanics, volumetric analysis of upper airway, or the possibility of virtual planning of treatment.

CONCLUSION

The application of tomographic exams and 3D imaging in Orthodontics and Maxillofacial Surgery is promising, overcoming many limitations of conventional radiographic methods. The generation of 3D CBCT models provides a great amount of information to the clinician, since measuring procedures are more precise and realistic, and structural magnification and superposure are avoided.

The three-dimensional superimposition method presented allows the assessment of important structural displacements following surgery, and its short and long-term stability. Despite all training, expertise, technical support, and time required, this methodology seems to have great validity for clinical, scientific and educational orthodontic and surgical application.

ACKNOWLEDGEMENT

Dr. Martin Styner and Dr. Guido Gerig, from the Department of Computer Sciences (UNC/Chapel Hill), for all scientific and technical support during the development and application of this methodology.

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Submitted: October 2008
Revised and accepted: May 2009

Contact Address
Alexandre Trindade Simões da Motta
Av. das Américas, 3500 - Bloco 7/sala 220
CEP: 22.640-102 – Barra da Tijuca - Rio de Janeiro/RJ
E-mail: alemotta@rjnet.com.br