EARLY ORTHODONTIC TREATMENT: IS THE BENEFIT WORTH THE BURDEN?

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3D IMAGING FOR EARLY DIAGNOSIS AND ASSESSMENT OF TREATMENT RESPONSE

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Three-dimensional image analysis from cone-beam computed tomography (CBCT) scans offers improved diagnostic information and, more importantly, it provides a better way to evaluate the changes created by treatment and the adaptive displacement and remodeling that occur (Cevidanes, 2005*a*). As new technologies are being applied to orthodontic clinical practice, the previous emphasis on 2D cephalometric analysis of hard tissue and dental occlusion relationships has shifted to using 3D technology to assess both soft and hard tissue facial relationships.

The new emphasis on soft tissues as the limiting factors in treatment and soft tissue relationships in establishing the goals of treatment combine to produce major changes in diagnosis and treatment planning. The shift away from the earlier emphasis on dental occlusion and hard tissue relationships establishes a new paradigm for our understanding of response to treatment in which cephalometric analysis plays a smaller role and clinical examination of facial proportions a more important one. Randomized clinical trials are beginning to provide data that will allow clinicians to consider the efficiency and the effectiveness of early (preadolescent) treatment versus later (adolescent) treatment. The challenge of 3D analysis of soft tissue growth and response to treatment remains, as soft tissue changes are determined by the muscles attached to the skeletal structures. The soft tissue surfaces from spiral CT, cone-beam CT, laser scanning or 3D photography only contain information about the skin and facial appearance; they do not allow us to assess the underlying muscles.

Although the growth of the face and jaws can be measured in two dimensions, structural changes at specific locations are not reflected sufficiently in cephalometric measurements (Tulloch *et al.*, 1990; Ghafari *et al.*, 1998; Harrell *et al.*, 2002; Togashi *et al.*, 2002; Turpin, 2002). The SNB angle has been called a poor indicator of the effectiveness of functional jaw orthopedics, because the increase in lower anterior facial height due to correction of a Class II relationship camouflages the concurrent increase in mandibular length. Nevertheless, in a recent systematic review of the literature, studies of mandibular changes produced by functional appliance in Class II malocclusion patients still report that the mandibular position to the cranial base as measured by the SNB angle was not impacted in a clinically significant way by functional jaw orthopedics (Cozza *et al.*, 2006).

During growth and/or response to orthopedic treatment, the mandibular rami and condyles develop in many directions relative to all possible individual variations in the nasomaxilla and middle cranial fossae anatomic patterns (Björk and Skieller, 1983, 1985; Coben, 1998; Wilhelm *et al.*, 2001). However, identifying the rami's role relative to skeletal compensations in maxillomandibular discrepancy corrections cannot be accomplished by analyzing population norms, angles or interlandmark distances (Lewis *et al.*, 1985; Dibbets, 1996).

The radiation dose in spiral CT (Mozzo *et al.*, 1998; Mah and Hatcher, 2004), the high cost of CT and magnetic resonance imaging (MRI; Kawamata *et al.*, 1998; Ludlow *et al.*, 2003; Cevidanes *et al.*, 2005*a,c*), and the lack of simple 3D image analysis tools for clinical use have limited their usefulness in the study of post-treatment changes. Recently, CBCT has been described as the 3D method of choice for maxillofacial imaging in dentistry because of the reduction in equipment needs, operating costs, radiation and acquisition time; the ability to obtain high-resolution imaging for facial bones and teeth; and the possibility to obtain from only one exposure the usual set of orthodontic lateral, frontal, panoramic or periapical radiographs (Mozzo *et al.*, 1998; Ludlow *et al.*, 2003; Mah and Hatcher, 2004). CBCT allows 3D reconstruction with complete visualization of the facial structures and the capacity to make measurements accurately within 0.36 mm in any direction (Cevidanes *et al.*, 2005*a*). Importantly, a quantitative assessment of condylar rotation/displacement that was not feasible previously with 2D technology now can be accomplished using CBCT scans.

Evidence that the rami and the condyles might play compensatory roles in skeletal growth and in response to orthodontic treatment comes from the findings of implant and histological studies (Björk and Skieller, 1983, 1985; Petrovic *et al.*, 1990). Quantitative descriptors of 3D rami skeletal compensations now can assess the manner of assembly of structural components involved in facial morphogenesis. The quantification of changes in skeletal morphology includes two significant developmental processes during bone growth: primary or secondary displacement and bone surface remodeling (Petrovic *et al.*, 1990). The alteration of landmark position during growth and treatment involves the simultaneous processes of bone surface remodeling, primary displacement by individual bone growth, and secondary displacement by the growth of adjacent structures. In this chapter we will present diagnostic findings, growth assessment and Fränkel Functional Regulator II treatment outcomes based on 3D imaging techniques.

VISUALIZATION AND MEASURING OF SUPERIMPOSED 3D MODELS

Imsel software, which was developed by the University of North Carolina (UNC) Department of Neurosurgery, is used to convert the *NewTom* DICOM files to a format (GIPL) that is readable by other public software imaging processing tools. Voxels are reformatted for an isotropic of 0.5 x 0.5 x 0.5 mm, avoiding increases in image file size that would require greater computational power and user interaction time. In addition, *Imagine* software (developed by UNC Computer Sciences) is used to compact the size of GIPL format files created with *Imsel*. From a set of more than 300 axial, lateral and anteroposterior cross-sectional slices for each image acquisition, the segmentation of the cranial base and mandible is performed with *InsightSNAP* (developed by UNC Computer Sciences). Segmentation is the process of constructing 3D models by examining cross-sections of a volumetric data set to outline the shape of structures (Cevidanes, 2005*a*). A key feature of the CBCT images is the ability to navigate through the volumetric data set in any of the orthogonal slice windows. After segmentation, a 3D graphical rendering of the volumetric object allows navigation between voxels in the volumetric image by zooming, rotating and panning.

To evaluate growth and treatment changes of a specific patient, images taken at different ages are superimposed using a fully automated method of voxel-wise registration to avoid observer-dependent location of points identified from overlap of anatomic landmarks. In that the growth of the anterior cranial fossae and the ethmoid bone is completed in early infancy, its surfaces are used in the registration procedure where the software compares the grey level intensity of each voxel between two CBCT images. In this way, the anterior cranial base of the CBCT images are used as reference for superimposing different time points (Fig. 1). As Baumrind and colleagues (1983) pointed out, these superimposition methods determine that the 3D changes described are relative to the individual cranial base, and not absolute displacement.

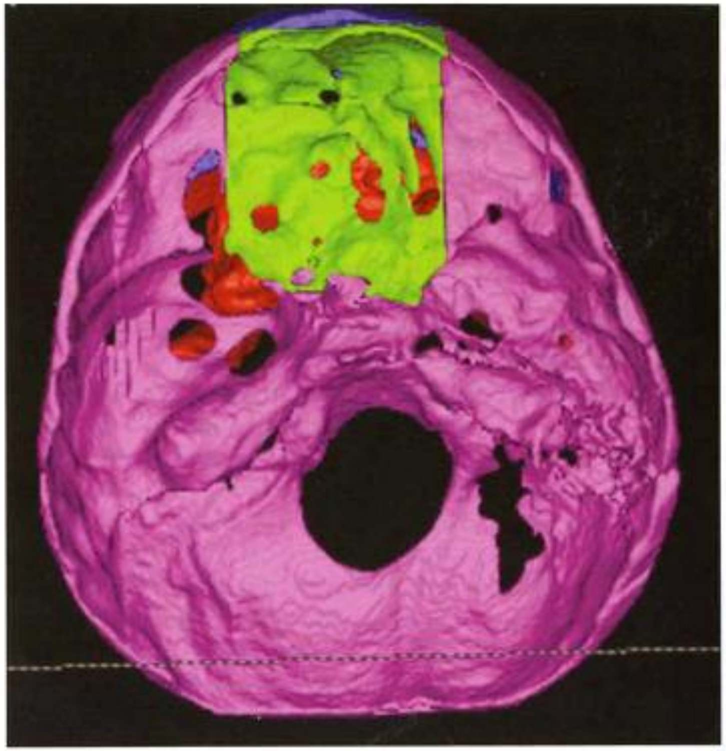

Figure 1. The superimpositions of 3D models of growing children differ from adult patients for which the whole surface of the cranial base is used for registration. For growth assessment we use the anterior cranial fossa surfaces for registration, as the superimpositions describe growth relative to the individual cranial base.

The next step in the analysis involves overlaying the 3D models surfaces with another tool, *i.e., Fltk/3DSOV,* which allows different degrees of transparency to visually assess the boundaries of the mandibular rami and condyles between superimposed models of two different time points. The visualization of the superimpositions clearly identifies the location, magnitude and direction of mandibular displacements, and allows quantification of vertical, transverse, and anteroposterior bone displacements and the remodeling that accompanies both growth and response to treatment.

Measurements of the surface distances between different phases can be computed in color-coded maps using the *MeshValmet* tool. This

procedure computes thousands of distances in millimeters between surface's triangles, and quantifies how much, on average, the two surfaces differ from each other. After combining all 3D models at various time points, specific regions of interest such as the chin prominence, condyles and the posterior border of the rami can be selected and analyzed.

The color maps can be used to indicate inward (blue) or outward (red) displacement between overlaid structures. Green indicates the absence of surgical displacement. For example, mandibular advancement forward displacement would be shown in red in the anterior surfaces and blue in the posterior surfaces. A medial displacement of the condyles and rami will display red medial surfaces and blue lateral surfaces. No post-surgical change would be green. This method has been published and used since 2004 (Bailey *et al*., 2004; Cevidanes *et al*., 2005*a*).

EARLY 3D DIAGNOSIS AND TREATMENT PLANNING

Applications of early 3D diagnosis in orthodontics include dental root inclination and torque, impacted and supernumerary tooth positions (Fig. 2), thickness and morphology of bone at sites of mini-implants for anchorage, and osteotomy sites in surgical planning. Findings such as resorption, hyperplasic growth, displacement, shape anomalies of mandibular condyles and morphological differences between the right and

Figure 2. The close relationship of upper canines and lateral incisors clearly can be seen with 3D reconstruction.

left sides emphasize the diagnostic value of computed tomography acquisitions. Furthermore, relationships between soft tissues and the airway can be assessed in three dimensions.

For cases of severe asymmetry, *e.g.*, hemifacial microsomia, knowing the degree of mandibular involvement is crucial in planning the timing and choice of treatment such as distraction osteogenesis, costocondral grafting, functional orthopedics or observation of growth until post-pubertal surgical reconstruction (Fig. 3). Treating these cases with early distraction osteogenesis has been controversial as it was not clear whether or not treating early makes a difference or whether facial asymmetry progresses with growth (Posnick, 1998; Kau *et al.*, 2006; Maeda *et al.*, 2006). In Figure 4, the growth superimpositions from a period of 1.5 years during the ascendant part of the pubertal growth spurt curve of a child who had previous costocondral grafting show changes in facial deformity that indicate surgical correction prior to completion of growth. Mirror images

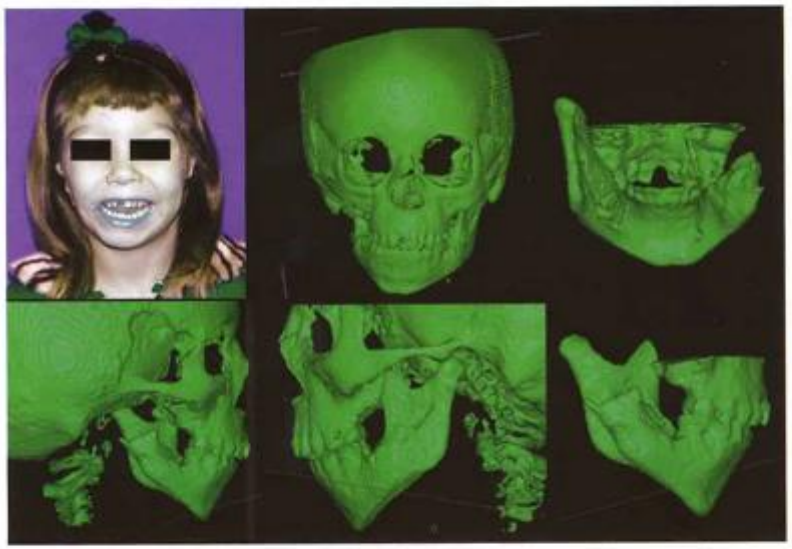

Figure 3. A four-year-old patient with hemifacial microsomia type 3 for whom important distraction osteogenesis treatment planning decisions need to be made. While a costocondral graft might establish a joint on the affected side, its future growth is unpredictable. For distraction osteogenesis, the challenge of

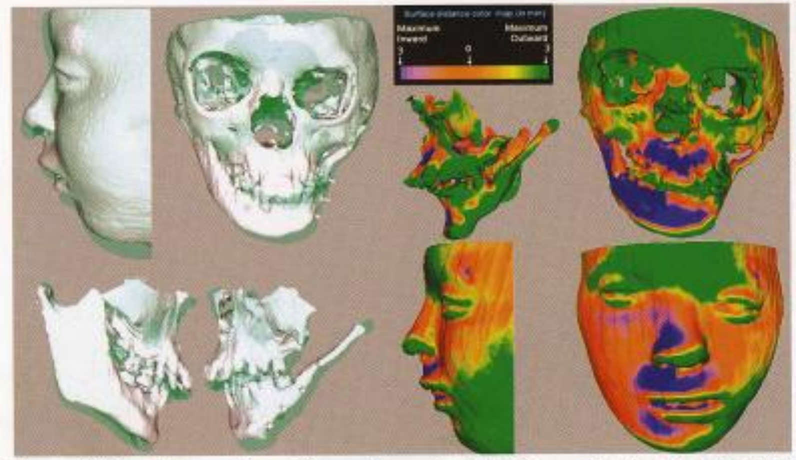

Figure 4. Growth superimpositions of a period of 1.5 years during the ascendant part of the pubertal growth spurt curve of a hemifacial microsomia patient who received a costocondral graft at 7.5 years of age. Registered on the anterior cranial fossa, the 3D models on the left show vertical and lateral growth through the semi-transparent overlay. The models in white were taken at age 9.5 years of age and in red at 11 years of age. The 3D models on the right show the 3D color maps of the surface distances between the two time points displaying the lateral growth of the costocondral graft.

of 3D models now can aid surgical planning and assessment of the severity of the asymmetry (Figs. 5-7; Chapuis *et al.*, 2004).

The radiographs conventionally used for orthodontic diagnosis, *e.g.*, lateral cephalograms and panoramic x-rays, might fail to early diagnose conditions such as supranumerary teeth (Fig. 8), odontomas (Fig. 9), and aid in the differential diagnosis of failure of eruption as shown in Figures 10 and 11.

← Figure 3. *Continued.*

stimulating growth in 3D still remains. For functional orthopedics the question is how much can the deficient/absent muscles on the affected side aid mandibular growth. A fourth option is to observe growth until post-pubertal surgical reconstruction.

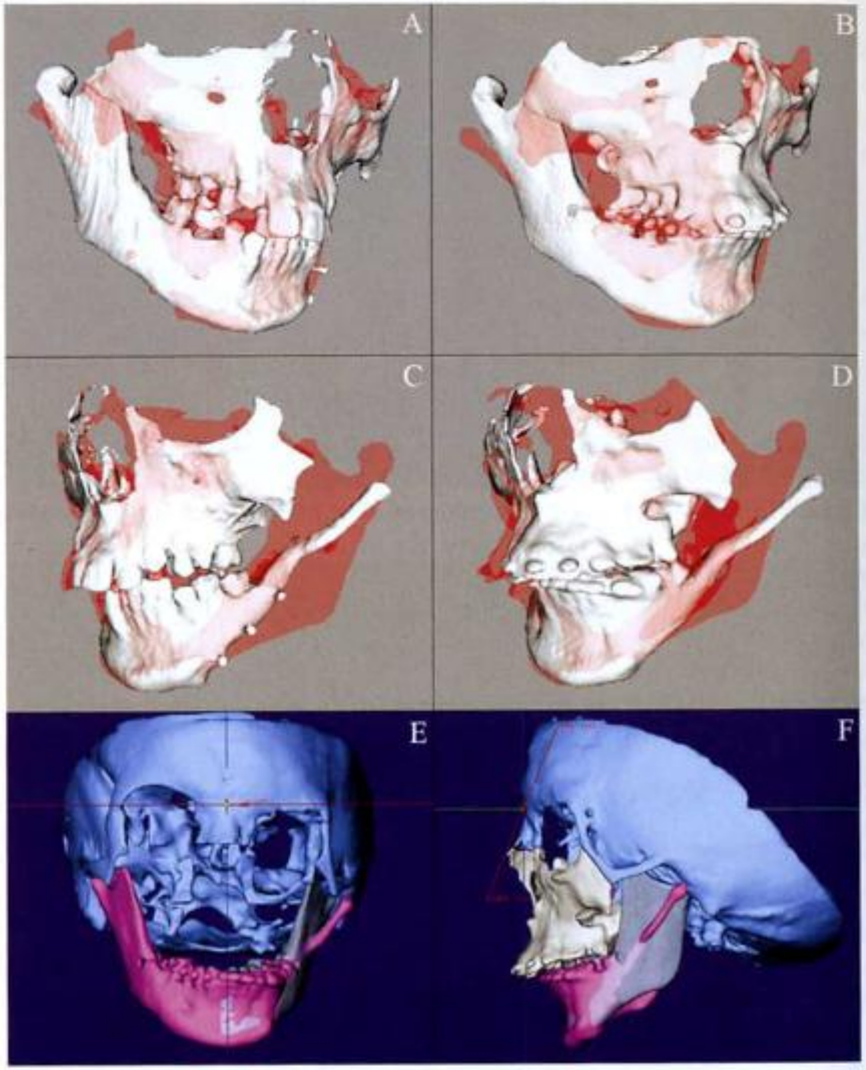

Figure 5. Mirror images of the 3D models. *A-D*: Left and right sides of the original model were inverted through a constructed midsagittal plane, building a mirror model that was superimposed on the actual patient model. The white models are the original images, and the mirror images are shown in semi-transparent red. The images on the left were taken at 9.5 years of age and on the

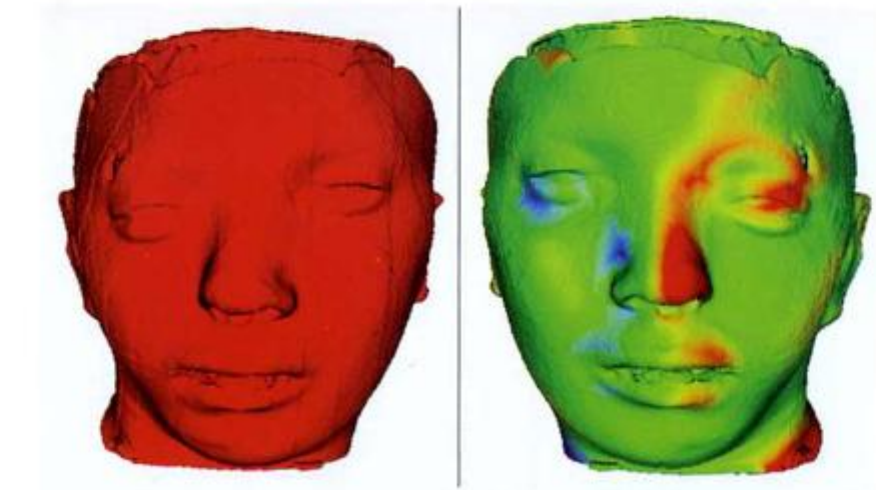

Figure 6. Visualization of right and left differences of soft tissue structures. The model in red shows the original patient's morphology, and the model in green shows the surface distances between the superimposition of the original relative to its mirrored image. Soft tissue asymmetry can be seen especially in the nasal and orbital regions.

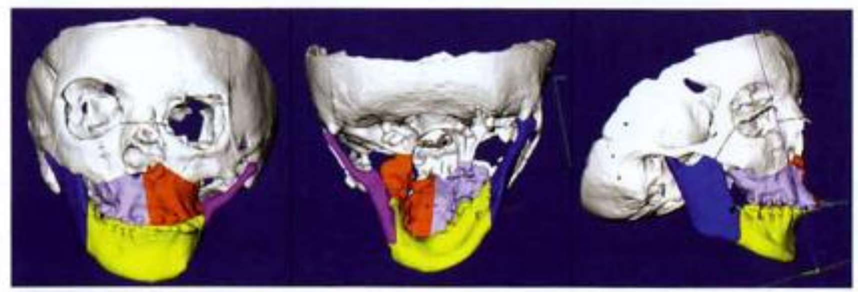

Figure 7. Surgical simulation with CMF tool to plan displacement of each of the colored segments (Chapuis *et al.*, 2004).

← Figure 5. *Continued.*

right at 11 years of age. *E and F*: The right side of the mandible was mirrored to the left using a CMF tool (Chapuis *et al.*, 2004). The lateral position of the costocondral graft and the absence of an articular fossa can be seen.

Figure 8. 3D imaging used for early diagnosis of a supranumerary tooth that could not be seen in the panoramic x-ray.

The peak adolescent growth spurt and early permanent dentition have been described as the gold standard for the timing of orthodontic treatment. This is because there is some growth (especially vertical growth) remaining to assist treatment, permanent teeth are available for final positioning, treatment usually ends as the adolescent growth spurt ends, and the shorter treatment time lowers the burden of treatment.

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Figure 10. Frontal and lateral views of a severe case of the failure of the posterior teeth to erupt that show the lingual inclination of premolars and molars.

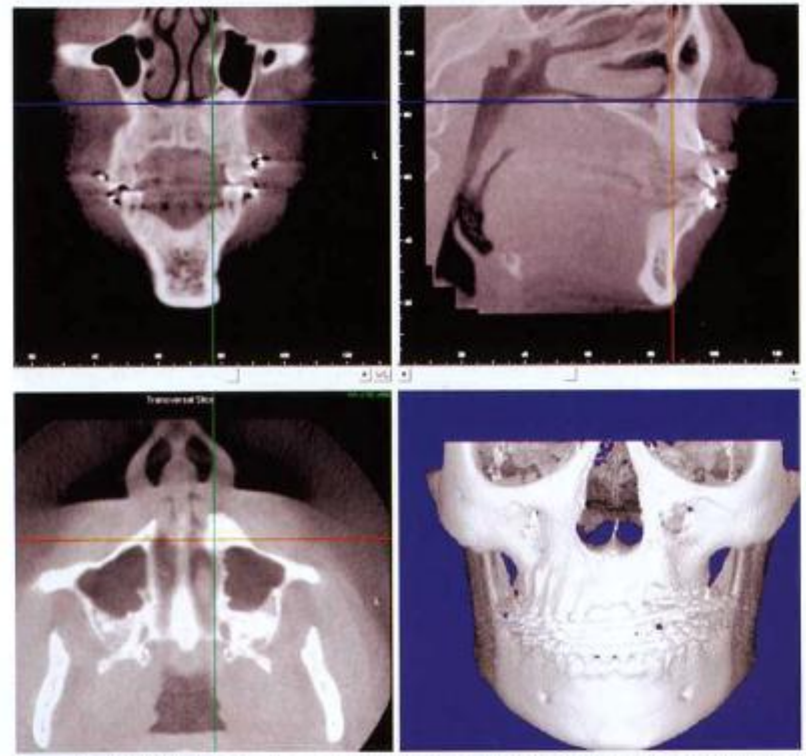
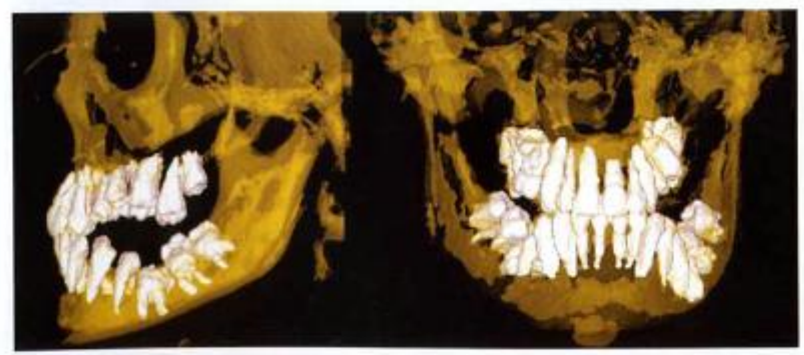


Figure 9. CBCT visualization with Dolphin 3D (Dolphin Imaging and Management, California) shows the presence of odontoma tooth apical to the upper left canine.



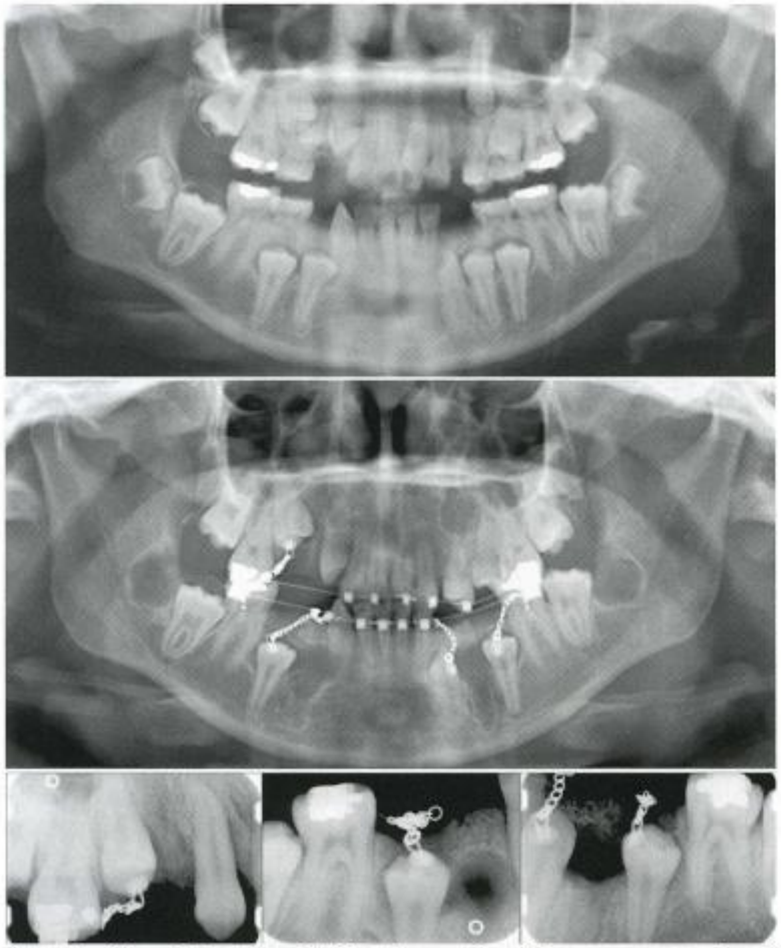


Figure 11. The orthodontist waited for the eruption of the permanent teeth until the patient was 16 years old, and then referred the patient as a failure of eruption case. Extraction of premolars and the upper left canine opened space for traction of the impacted teeth.

The question of whether it is advantageous to treat before or after the gold standard time now can be addressed using 3D imaging. We have recently used 3D imaging to investigate changes, relapse and stability after surgical correction for both late teen and adult treatment and relapse and stability after treatment with the Fränkel Regulator II during the ascendant part of the growth spurt curve (Fig. 12).

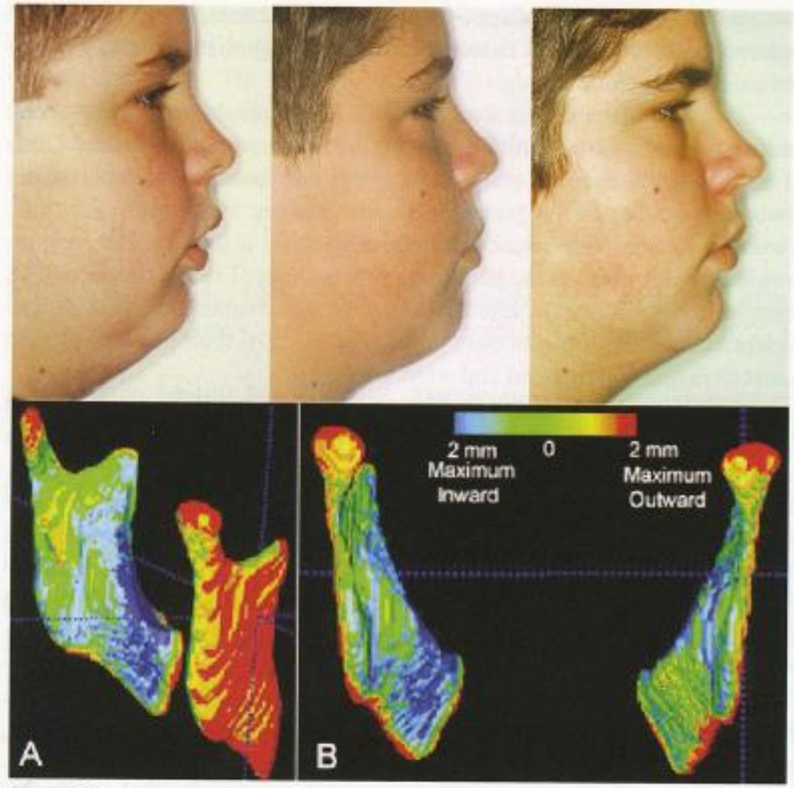


Figure 12. Pretreatment profile changes (*upper left*), after treatment with the Fränkel Regulator II appliance (*upper middle*) and two-years post-treatment (*upper right*). The color maps of the superimposition of pre- and post-treatment MRIs show the vertical, lateral and anterior growth of the mandibular rami.

3D ASSESSMENT OF MANDIBULAR GROWTH AND RESPONSE TO ORTHOPEDIC TREATMENT

We have applied generalizable methods for 3D landmark data, focusing on the morphogenic basis of Class II malocclusion. We addressed the biologic question of whether mandibular rami growth is altered relative to its equivalents by using 3D imaging to measure the changes in the mandibular rami relative to how far the middle cranial fossae places the nasomaxillary complex anteriorly and how widely it places the two condyles bilaterally (Björk and Skieller, 1983; Bhat and Enlow, 1985; Cevidanes *et al.*, 2003). We used 3D magnetic resonance imaging to study relationships among craniofacial components during the pubertal growth spurt and in response to Fränkel appliance therapy (Cevidanes *et al.*, 2005*b*).

The subjects in this study were 78 Brazilian children, 28 of whom were treated for Class II malocclusions, 25 of whom had untreated Class II malocclusions and 25 children who had untreated normal occlusions. Two high-resolution magnetic resonance images with 1 mm isotropic voxel resolution were taken for each subject for a total of 156 images; one image was taken at the beginning of treatment (T1) and the second 18 months post-treatment or after an 18-month observation period (T2). Developmentally, all subjects were at the beginning of their pubertal growth spurt as diagnosed by hand and wrist x-rays.

We used a Procrustes geometric transformation of 3D skeletal landmarks to assess growth or treatment alterations from T1 to T2. The standard biometric approach of Procrustes, more than a description relative to stable intraosseous reference points like implants, analyzes the relative displacement of key counterpart components during growth and response to treatment. Therefore, the Procrustes fit of each subjects' landmark coordinates showed the displacement of landmarks relative to all landmarks included in the 3D models, controlling for the variations in rotation, translation, and scale (Slice, 2001).

Not only were the principal dimensions of skeletal alterations different for treated and untreated Class II and normal-occlusion subjects, but the PCA scattergrams also showed considerable individual variability in growth and response to treatment alterations (Chen *et al.*, 2002). A remarkable product of this study was the visualization using deformation grids of the underlying 3D patterns of relative skeletal alterations of the mandibular rami. The non-significant configuration changes from T1 to T2 in the deformation grids for both the untreated Class II controls and the normal-occlusion subjects showed maintenance of the landmark configuration with growth, with slight relative mandibular advancement characteristic of the differential maxillary/mandibular growth at the beginning of the pubertal growth spurt. For the treated group, the skeletal alterations visualized in the T1-T2 deformation grids were significantly different: *P* _ .001 for treated Class II subjects *vs.* untreated Class II controls and for treated Class II subjects *vs.* subjects with normal occlusions. The differential anteroposterior location of 3D landmarks observed in the deformation of coronal/axial gridlines showed more forward (anterior) rami alignment relative to their counterparts in the posterior nasomaxilla and the middle cranial fossae. The deformation grids also showed differential vertical location of landmarks with increased relative mandibular rami vertical dimension. The striking statistically significant 3D skeletal alterations shown graphically by the deformation grids are considered a favorable skeletal response to treatment with the Fränkel Regulator II aimed at increasing relative mandibular growth.

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