THE CUTTING EDGE

(Editor's Note: This quarterly column is compiled by JCO Technology Editor Ronald Redmond. To help keep our readers on The Cutting Edge, Dr. Redmond will spotlight a particular area of orthodontic technology every three months. Your suggestions for future subjects or authors are welcome.)

To help you understand the technological advancement represented in this month's Cutting Edge column, I need to describe briefly one of my passions—astrophotography. With the camera mounted on a telescope, exposures of 30-45 minutes are not uncommon. Until recently, I had to compensate for the inaccuracies of the telescope's worm gear and equatorial mount by using a guide scope and joystick to track another object, a "guide star". Today, however, the telescope's computer selects the guide star and locks it to one pixel. Digital technology has freed me of the bone-chilling experience of sitting outside for hours to take a picture.

Similarly, Drs. Choi and Mah have developed a technique of voxel superimposition that has automated the cumbersome (and frequently inaccurate) superimposition of computed-tomography volumes. I hope you enjoy their article—I know you will enjoy the ease of superimposition that their technique has provided for our profession.

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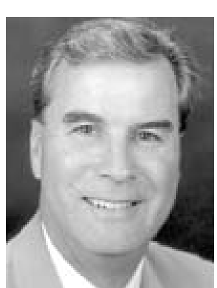
A New Method for Superimposition of CBCT Volumes

When orthodontists use superimpositions of lateral cephalometric tracings to assess growth and treatment outcomes, the ABO recommends that they be registered, for the craniofacial composite, on the outline of sella turcica with best fit on the bony structures of the anterior cranial base; for the maxilla, on the lingual curvature of the palate with best fit on the maxillary bony structures; and for the mandible, on the internal cortical outline of the symphysis with best fit on the mandibular canal.[1]

Image fidelity and landmark selection and identification are critical in performing these superimpositions. In a recent study, the ABO maxillary method was found to underestimate vertical displacement and overestimate forward movement of maxillary landmarks compared with Björk's technique involving metallic implants.[2] Super-



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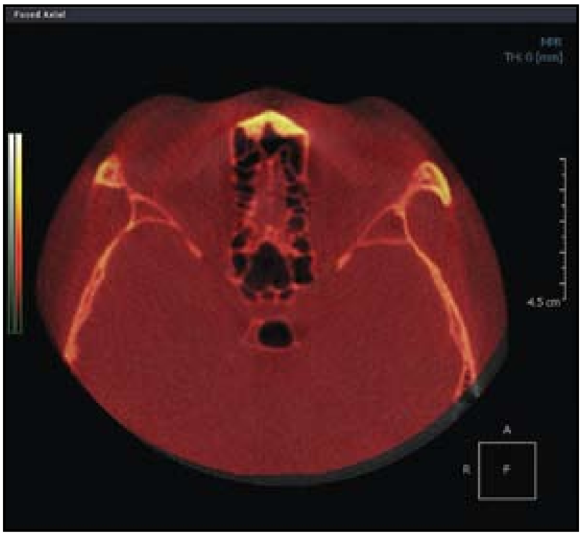

Fig. 1 Superimposed axial slice images of anterior cranial base before and after orthognathic surgery. Ethmoidal air cells and other fine anatomic structures are perfectly registered.

imposition on the internal cortical outline of the symphysis and the inferior alveolar nerve canals generally approximated mandibular superimpositions on implants, although the lower anterior border of the symphysis might have been preferable; superimposition on the lower border of the mandible did not accurately reflect the actual pattern of mandibular growth and remodeling.

In another study comparing the superimposition methods of Björk with those of Steiner and Ricketts, significant differences were observed in the reference landmarks (sella, nasion, basion, or pterygomaxillare) used for superimpositions.[3] Most landmarks were displaced similarly with the Björk and Ricketts methods in the horizontal plane, but their vertical displacement differed. The direction of displacement of sella and pterygomaxillare varied according to the procedure.

In a third study, superimposition at the occipital condyles (defined as I-point, I-curve), oriented to the anterior cranial base, seemed to be the most accurate means of assessing growth-related changes.[4] Differences in superimposition methods must therefore be considered when evaluating growth- and treatment-related changes.

The introduction of cone-beam computed tomography (CBCT) in orthodontics has now created an opportunity to perform superimpositions in three dimensions and thus eliminate some of the errors created by traditional lateral cephalometric tracings. Cevidanes and colleagues tested superimpositions of three-dimensional CBCT, using several software programs[5,6] to produce overlays with color-coded structures that would show the magnitude of displacements between two time points. This fully automated system, with registration on the cranial base, was largely independent of observer error. Comparison between two presegmented surface models was possible, but superimposition of volume images or slices was not recommended.

Recent software developments now allow both visualization and superimposition of volumes and slices. Some of these methods require landmark registration, however, which increases the risk of observer-dependent errors. Fine features of the cranial base are also difficult to visualize on CBCT volumes, further complicating landmark identification.

In this article, we present a method for comparison of CBCT images that allows accurate, rapid, automatic superimposition without prior segmentation or landmark designation. Boolean operations can be used to generate new image sets, which can then be used to evaluate treatment- and growth-related changes.

Theoretical Background

This new method borrows a basic concept from information theory—mutual information (MI), or relative entropy—as a matching criterion. The use of MI in superimposition was first suggested for registration of 3D CT images, magnetic resonance imaging, and positron-emission tomography of the brain for a single object.[7] MI is related to entropy by the equations:

1. $I(A,B) = H(A) + H(B) - H(A,B)$
2. $ = H(A) - H(A|B)$
3. $ = H(B) - H(B|A),$

where $H(A)$ and $H(B)$ are the entropy of A and B, respectively; $H(A,B)$ are their joint entropy; and $H(A|B)$ and $H(B|A)$ are the conditional entropy of A (given B) and of B (given A), respectively. $H(A)$ is thus a measure of the amount of uncertainty about the variable A, while $H(A|B)$ is the amount of uncertainty remaining in A when B is known. In equation 2, $I(A,B)$ is the reduction in uncertainty of the variable A resulting from knowledge of another variable B or, equivalently, the amount of information that B contains about A.

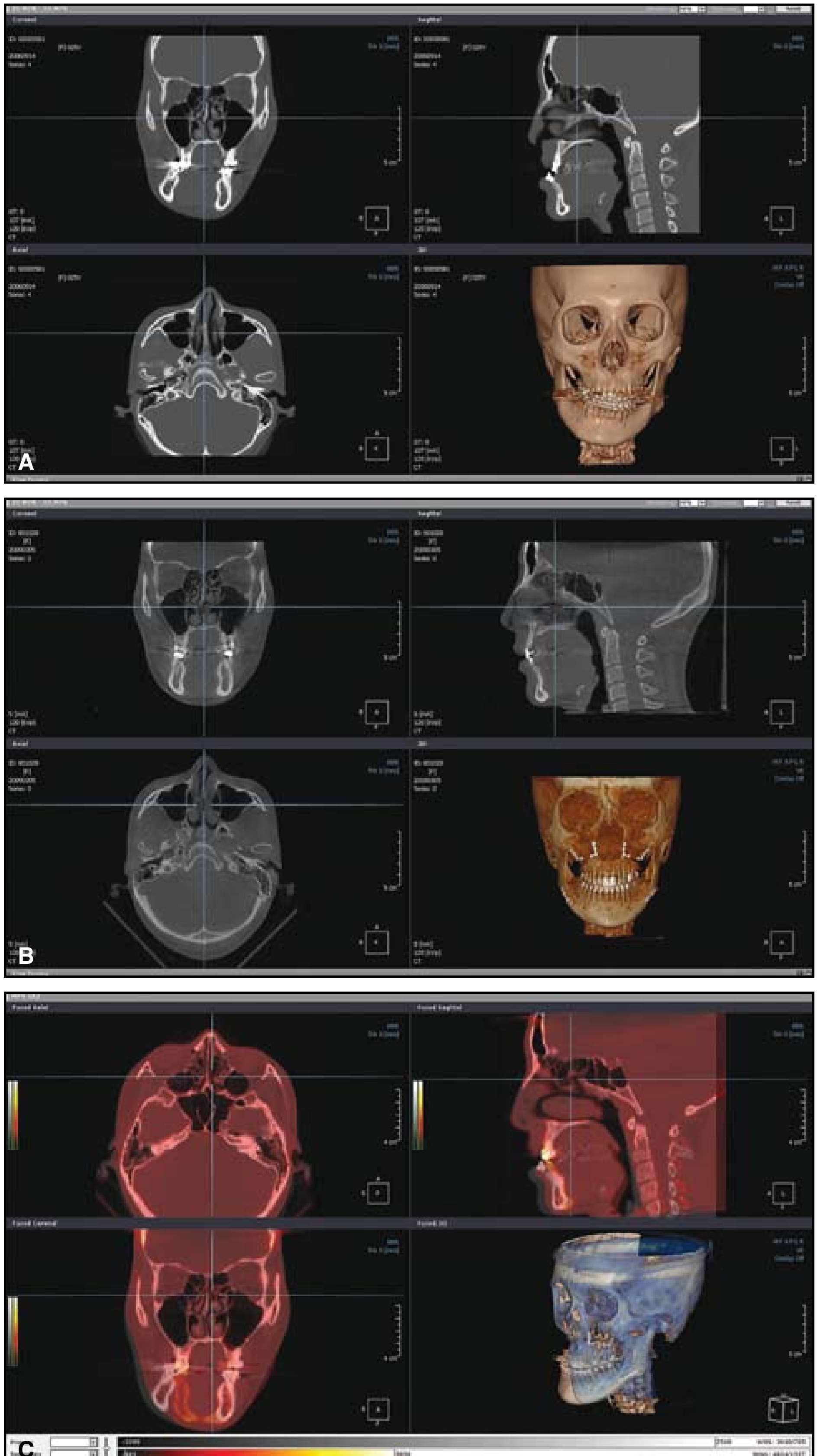

Fig. 2 Superimpositions of different CT modalities in same patient (Table 1). A. Multidetector helical CT, showing skeletal Class III malocclusion and facial asymmetry before surgery. B. CBCT of same patient after surgery. C. Superimposed multiplanar views and volume images of A and B; note complete correspondence of registrations in cranial base area.

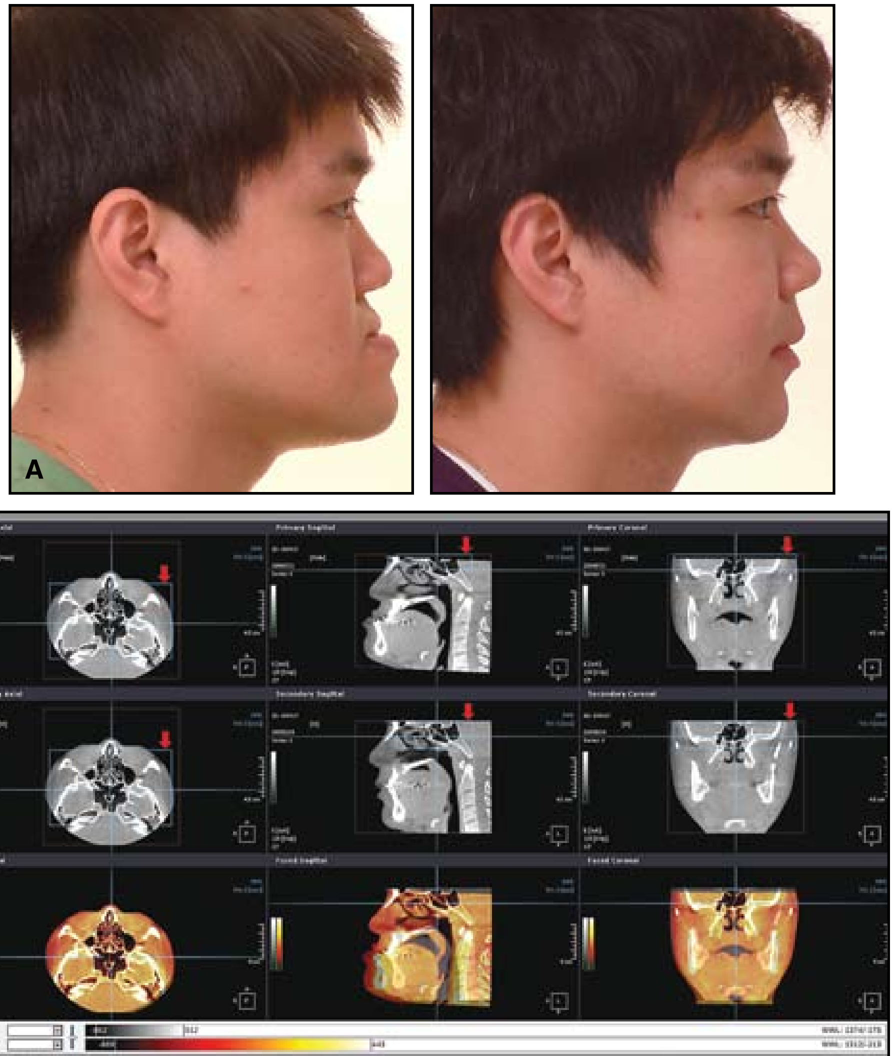

Fig. 3 Case 1. 26-year-old male with skeletal Class III malocclusion. A. Before and after orthognathic surgery. B. Top and middle rows: pre- and postsurgical CBCT images, with CBCT registration area shown within blue dotted lines in cranial base (red arrows). Bottom row: superimposed presurgical (red) and postsurgical (yellow) data (continued on next page).

If A represents the information about the cranial base in the pretreatment CBCT, and B represents the same information in the post-treatment scan, then as the correlation between A and B becomes higher, $H(A|B)$ or $H(B|A)$ becomes smaller. If the cranial base areas from two scans are geometrically aligned, $H(A|B)$ or $H(B|A)$ is minimized and MI is maximized in equations 2 and 3. Superimposed CBCT data can thus be generated by maximizing MI through translation and rotation of images.

Cevidanes and colleagues used this method to obtain geometrical information from one software program and then apply it in another for comparison of presegmented surface models.[6] We expanded the procedure to include volume and slice imaging and refined the algorithm and user interfaces. The result is a fast and accurate method for superimposing various images in one program.

Advantages

The MI registration described above provides subvoxel accuracy and highly robust registration.[6,7] Figure 1 shows superimposed axial images of CBCT data before and after orthognathic surgery. The axial slice displaying the anterior cranial base was selected because this region does not change with surgery. The perfect fit of the ethmoidal air cells reflects the extreme accuracy and precision of this superimposition compared to surface-based methods.

Another major advantage of this method is that CBCT and CT data sets generated by different

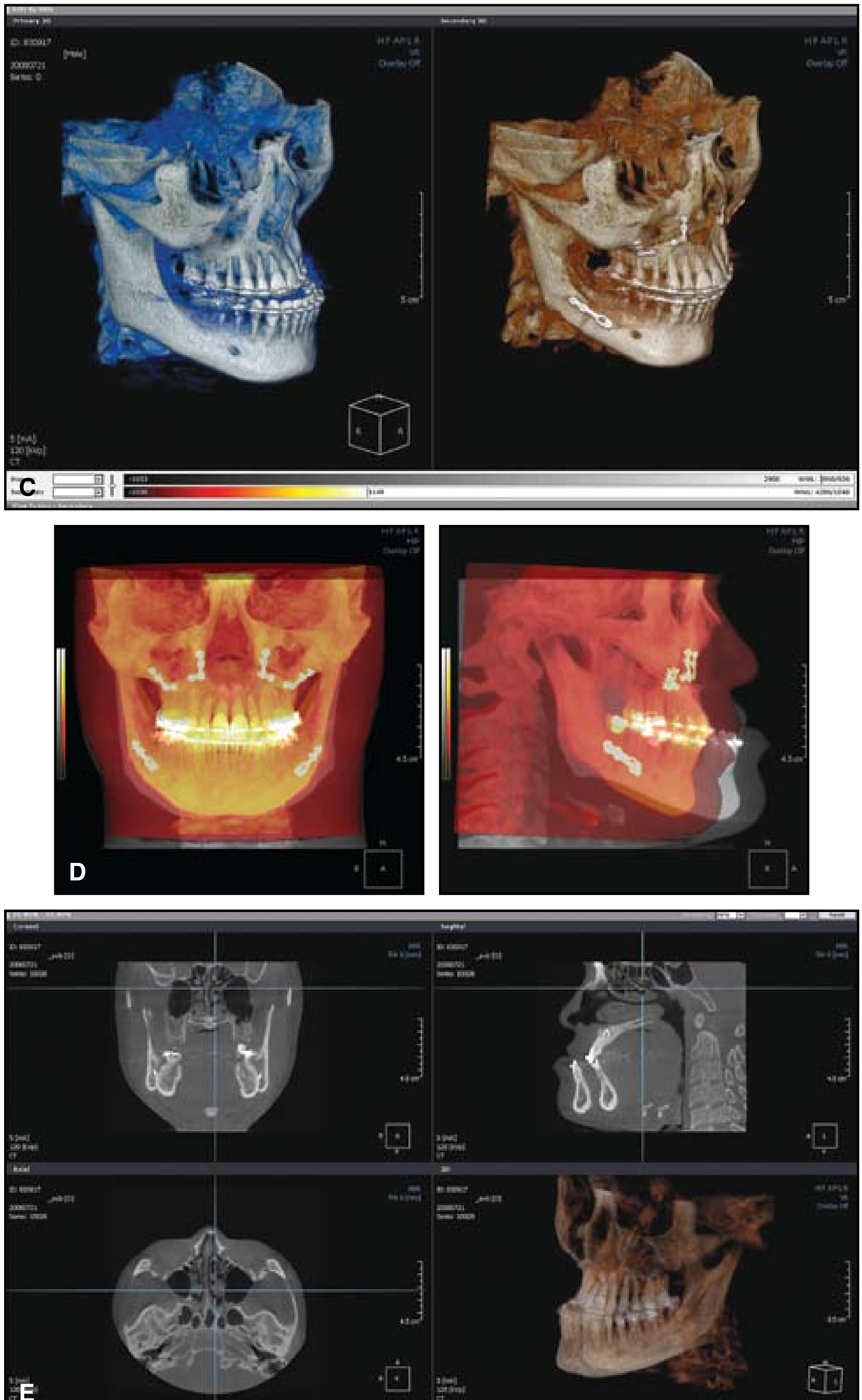

Fig. 3 Case 1 (cont.) C. Volume rendering of CBCT data. D. Superimposed postero-anterior and lateral cephalograms automatically generated from CBCT images. E. New image set created by combining pre- and postsurgical data in DICOM format **(continued on next page).**

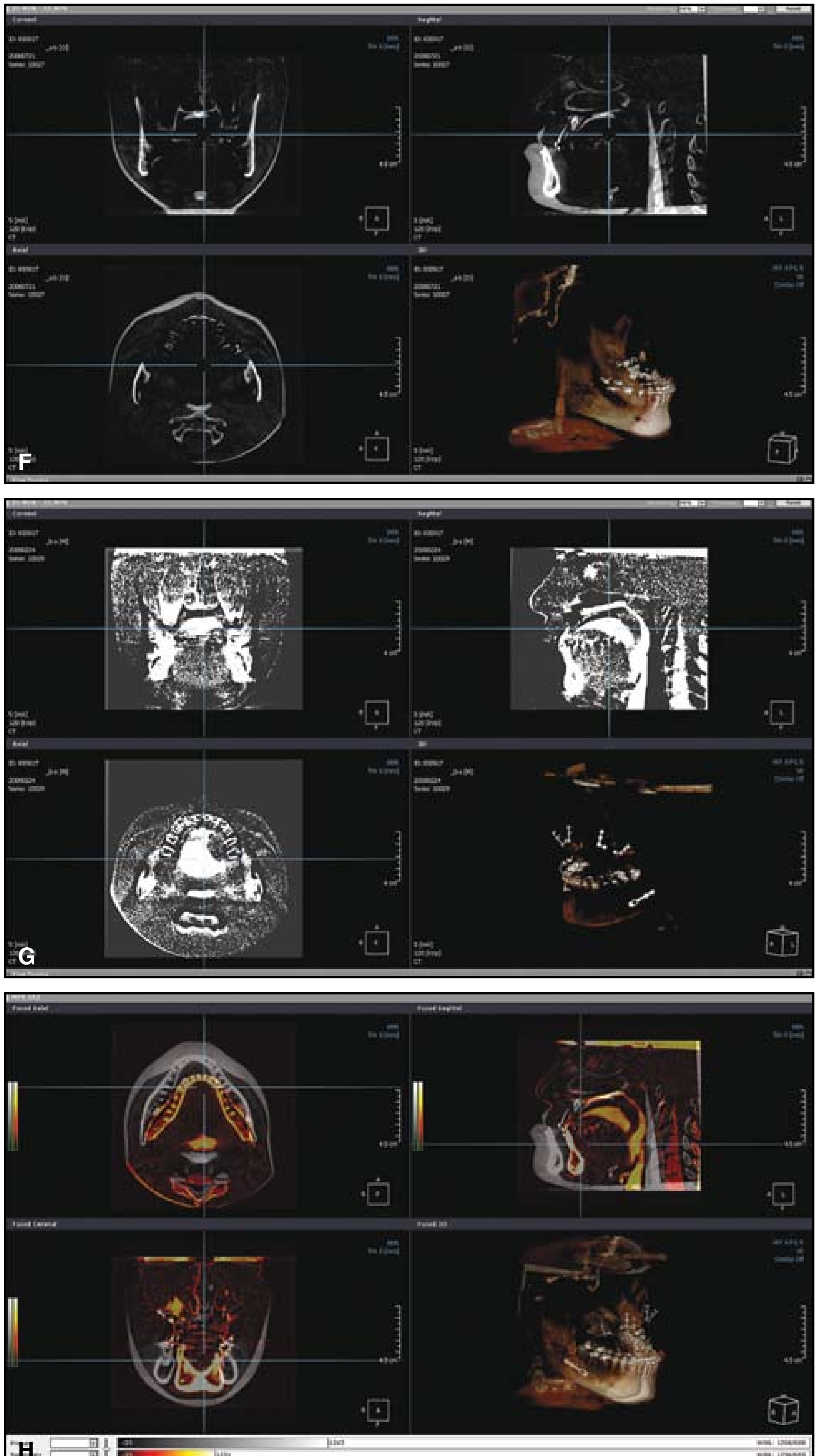

Fig. 3 Case 1 (cont.) F. New image set created by subtracting postsurgical from presurgical data (cranial base area not shown because subtraction removed registered area); note that two supernumerary maxillary teeth were removed during surgery. G. New image set created by subtracting presurgical from postsurgical data; note surgical plates and screws. H. Superimposition of F and G, accentuating changes in anatomical structures from orthognathic surgery (subtraction removed unchanged area).

TABLE 1
CT PARAMETERS FOR SUPERIMPOSITIONS IN FIGURE 2

	Before Surgery	After Surgery
Device model	SOMATOM Sensation 10***	3D eXam†
Device type	Multidetector helical CT	Cone-beam CT
mA	107	5
kVp	120	120
Patient position	Supine	Upright
Voxel size	0.336 × 0.336 × 1.0mm	0.3 × 0.3 × 0.3mm
Dimension	512 × 512 × 187 voxels	768 × 768 × 540 voxels
Grayscale	12 bits	14 bits

devices, protocols, voxel sizes, and grayscales can be superimposed (Fig. 2, Table 1). If lateral cephalograms are not produced from the same unit, it is extremely difficult, if not impossible, to superimpose them due to differences in magnification, head position, image production, and cephalostat geometry. CBCT and CT images are not subject to these limitations.

Procedure

The operator first designates the registration area, such as the cranial base, on the multiplanar slice images (Fig. 3B). The software then automatically calculates the best registration area by maximizing MI as described above. This step takes three to 10 seconds, depending on anatomical complexity and processing capability.

Superimposed data can be further analyzed within the same software program (OnDemand 3D*) or exported elsewhere in a Digital Imaging and Communications in Medicine (DICOM)** format. Numerous combinations of data sets, such as unions and subtractions, can be created using Boolean operations (Fig. 3E-H) and then exported. Post-treatment CBCT data can also be realigned and resliced to match the orientation of pretreatment data. Because unaltered structures can be removed if desired, this is a powerful means of visualizing changes related to growth or treatment.

Case 1

A 26-year-old male patient with a skeletal Class III malocclusion underwent a maxillary Le Fort I procedure and mandibular bilateral sagittal split ramus osteotomy (Fig. 3). Surgical results were evaluated with multiplanar image superimposition and selected 3D perspectives. Traditional postero-anterior and lateral cephalometric superimpositions can be generated automatically from the CBCT data if desired (Fig. 3D), reducing observer-dependent errors such as landmark misidentification.

Case 2

Figure 4 shows a young adult female patient with a skeletal Class II malocclusion before and after orthognathic surgery. Using a corrected CT along the condylar axis and volume imaging generated from CBCT superimposition, we evaluated both the mandibular condyles, to ensure that they were seated in the same position, and the mandible, to verify its counterclockwise autorotation (Fig. 4D). CBCT superimposition also allows accurate comparison of airway images at the same axial level (Fig. 4E,F).

Case 3

A 12-year-old female in the mixed dentition presented with ectopically erupting maxillary canines and generally short dental roots (Fig. 5). After CBCT was performed at the initial visit, the deciduous canines were extracted. Superimposition of the original data with those obtained one year later clearly shows that the eruption paths of the canines were outward and distal (Fig. 5C).

Conclusion

This method of superimposing CBCT volumes resolves the problems of image fidelity and

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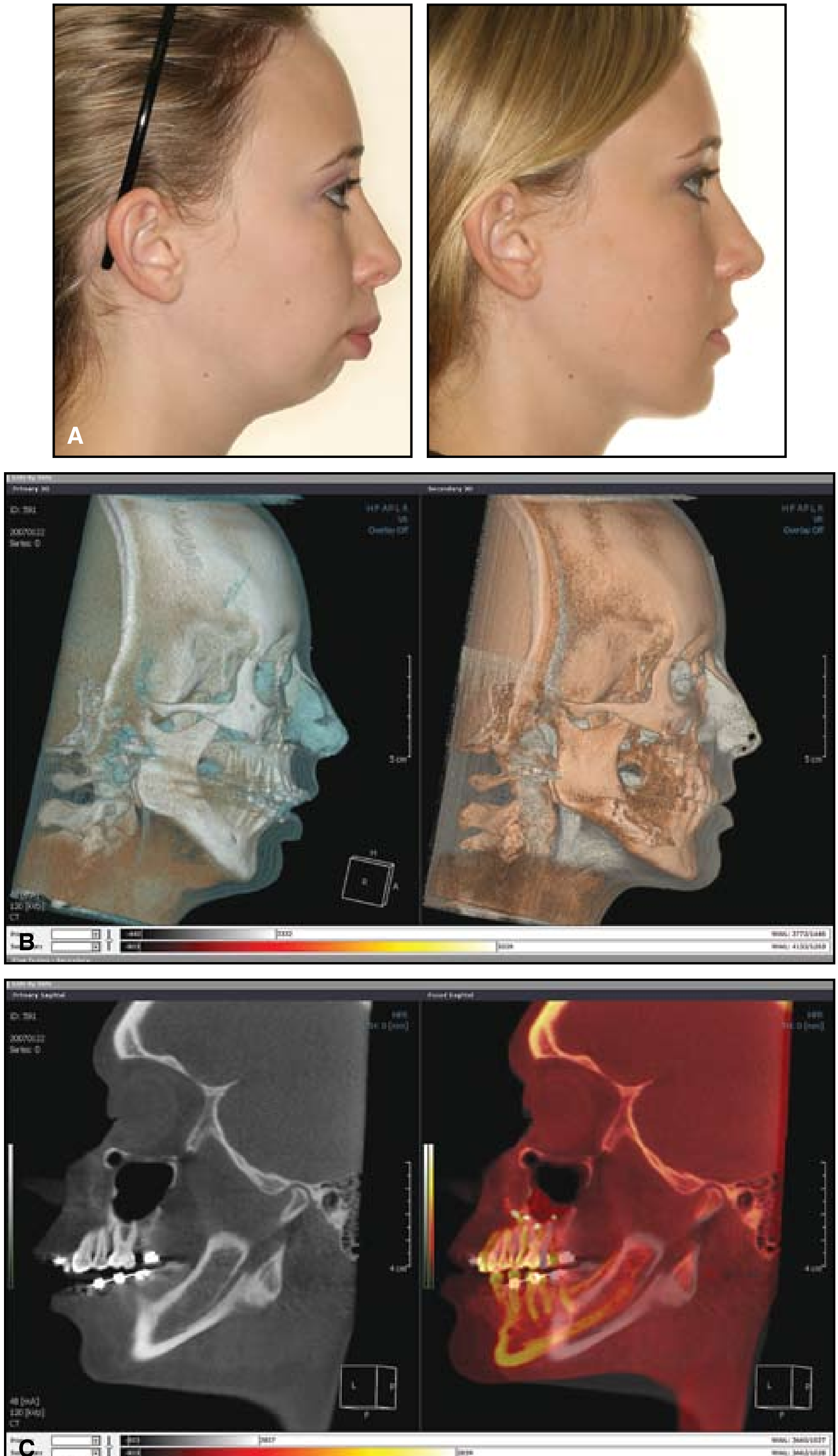

Fig. 4 Case 2. Young adult female patient with skeletal Class II malocclusion. A. Before and after orthognathic surgery. B. Volume renderings of CBCT data. C. Corrected tomogram of right mandibular condyle generated from CBCT data before surgery (left) and superimposed with postsurgical findings (right, with postsurgical in yellow) (continued on next page).

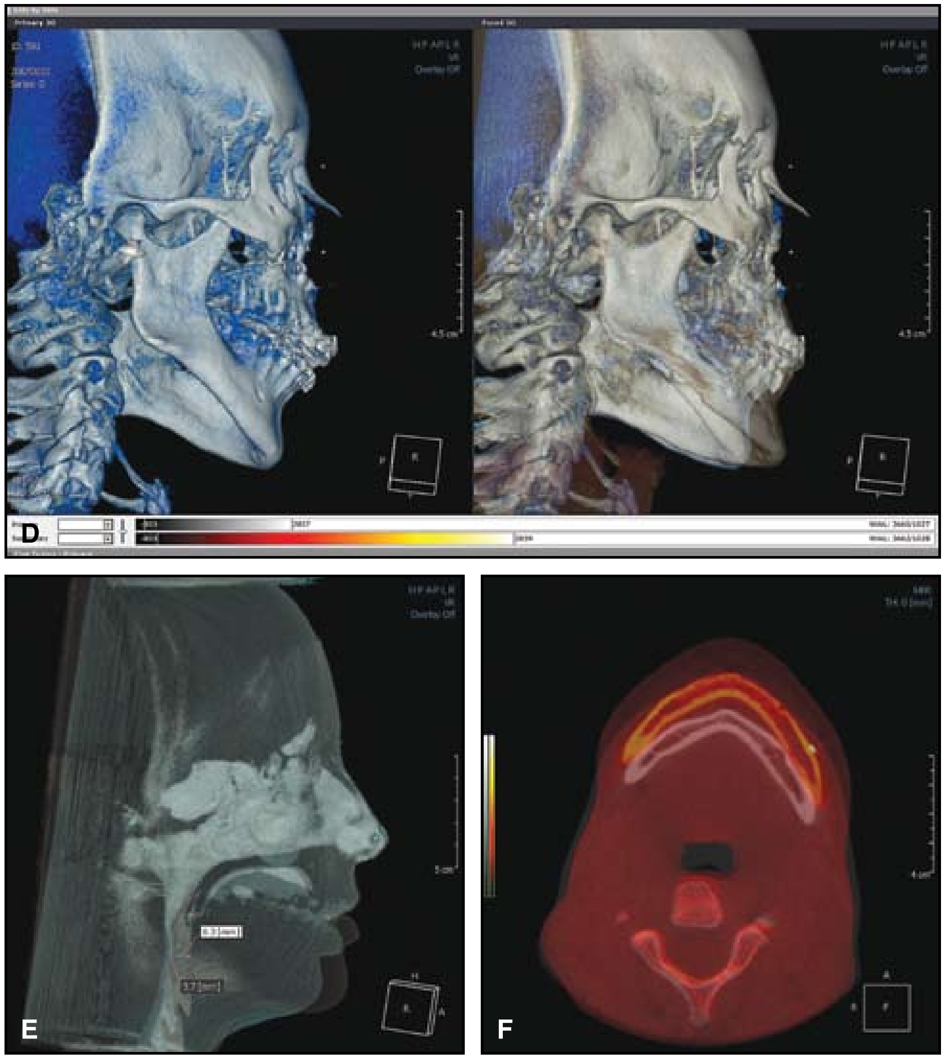

Fig. 4 Case 2 (cont.) D. Volume renderings before (left) and after surgery (right). E. Superimposition of airway volumes. F. Superimposition of slice images; note size of airway before and after orthognathic surgery. Cervical vertebrae do not align because of different head postures between scans (volume registered at cranial base). (Photos and CBCT data courtesy of Dr. G. William Arnett.)

landmark identification that have confounded clinicians for years with lateral cephalometric tracings. Reliable imaging and superimposition techniques now offer accurate, reproducible measurements for use in both research and clinical practice. This might allow us to address some of the long-standing controversies in orthodontics, including the mechanism of functional appliances, the effectiveness of nonextraction treatment and molar distalization, and the effects of orthodontics on the TMJ, among many others.

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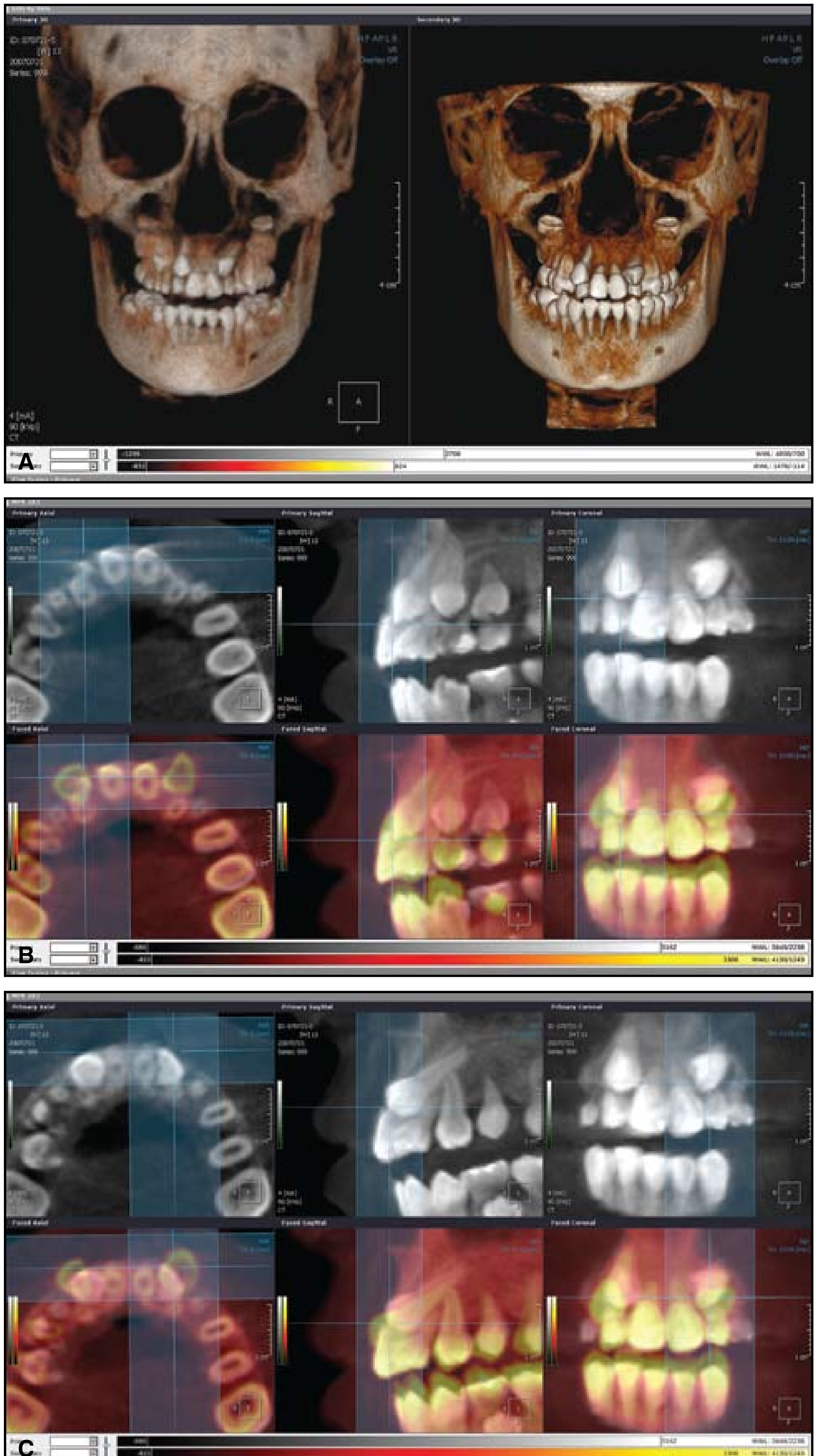

Fig. 5 Case 3. 12-year-old female with ectopically erupting maxillary canines. A. Volume renderings of CBCT images taken at ages 12 (left, T1) and 13 (right, T2) with different devices. B,C. Multiplanar images at T1 (top) and superimposition (bottom, with T2 in yellow); crosshairs indicate location of right canine tip (B) and left canine tip (C) at T1. Eruption path can be clearly identified in superimposed images. (CBCT data courtesy of Dr. Jeong-Hwa Lee.)