Three-dimensional cephalometry: Spiral multi-slice vs cone-beam computed tomography

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Three-dimensional (3D) craniofacial imaging techniques are becoming increasingly popular and have opened new possibilities for orthodontic assessment, treatment, and follow-up. Recently, a new 3D cephalometric method based on spiral multi-slice (MS) computed tomography (CT) was developed and validated by our research group. This innovative 3D virtual approach is a bridge between conventional cephalometry and modern craniofacial imaging techniques and provides high-quality, accurate, and reliable quantitative 3D data. The aim of this article was to describe the advantages and the disadvantages of spiral MS-CT 3D cephalometry and to discuss the potential of cone-beam CT 3D cephalometry. (Am J Orthod Dentofacial Orthop 2006;130:410-6)

Digital orthodontic technology opened new possibilities for patient diagnosis, treatment planning, follow-up, and outcome analysis. However, there is still an overwhelming need for accurate and effective craniofacial imaging modalities in patient care, education, and research.[1] Recently, a new voxel-based 3-dimensional (3D) cephalometry method was developed by our research group.[2,3] From a single computed tomography (CT) data set, virtual lateral and frontal cephalograms are computed and linked with both hard- and soft-tissue 3D surface representations. This innovative 3D virtual approach allows the setup of a precise and reproducible 3D cephalometric reference system[4,5] and accurate and reliable definition of 3D cephalometric hard-[6] and soft-[7] tissue landmarks. Voxel-based 3D cephalometry was developed and validated by using spiral multi-slice CT (MS-CT) data.[2] Recently, however, a new generation of dentofacial imaging systems based on cone-beam CT (CBCT) scanning, was introduced, and it has already made major contributions to dentofacial imaging.[8-14] The purpose of this article was to discuss the advantages and the disadvantages of spiral MS-CT 3D cephalometry and the potential of CBCT 3D cephalometry.

How MS-CT 3D cephalometry works

The patient's head is scanned according to a strict standardized scanning protocol (see below), while the patient is in a horizontal position. The CT images are stored by using digital imaging and communications in medicine (DICOM) 3.0 as a medical-image file format into a commercially available Windows XP personal computer (Pentium IV, 2.4 GHz, 512 MB, calibrated 17-in color monitor, resolution 1280 × 1024 pixels, NVIDIA (Santa Clara, Calif) GeForce4 Ti 4400 graphics card) graphics workstation. Then the DICOM files are converted into mxm files (Maxilim version 1.3.0, Medicim NV, Sint-Niklaas, Belgium). The bone and soft-tissue surfaces are segmented by applying a threshold on the acquired image volume of radiographic densities expressed in Hounsfield units (HU). To begin the analysis, the segmented hard- and soft-tissue surface representations of the skull are rendered in a virtual scene. After semiautomated virtual standardized positioning of the skull, high-quality virtual lateral and frontal cephalograms are computed as orthogonal projections from the single CT data set and linked to the 3D hard- and soft-tissue surface representations (Figs 1-3). This innovative 3D virtual scene approach allows (1) the accurate and reliable 3D definition of nasion (N) and sella (S) landmarks; (2) the generation of the anterior cranial base (S-N) plane and the setup of an accurate and reliable anatomic Cartesian 3D cephalometric reference system (Figs 4 and 5); (3) the accurate and reliable definition of 3D cephalometric hard- and soft-tissue landmarks (Figs 6 and 7); (4) the setup of 3D cephalometric planes; and (5) an accurate and reliable 3D cephalometric hard- and soft-tissue analysis. Table I shows the step-by-step 3D virtual approach to MS-CT 3D cephalometry of hard and soft tissues.

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The author is a stockholder in Medicim and has filed a patent application.
Submitted, August 2005; revised and accepted, November 2005.
0889-5406/$32.00

doi:10.1016/j.ajodo.2005.11.035

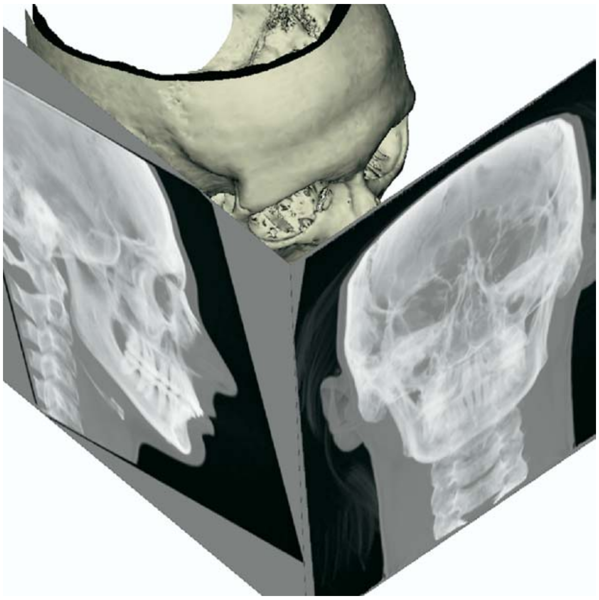

Fig 1. Virtual lateral and frontal cephalograms linked to 3D hard-tissue surface representation of skull (MS-CT).

Fig 2. Close-up view of virtual lateral cephalogram (MS-CT).

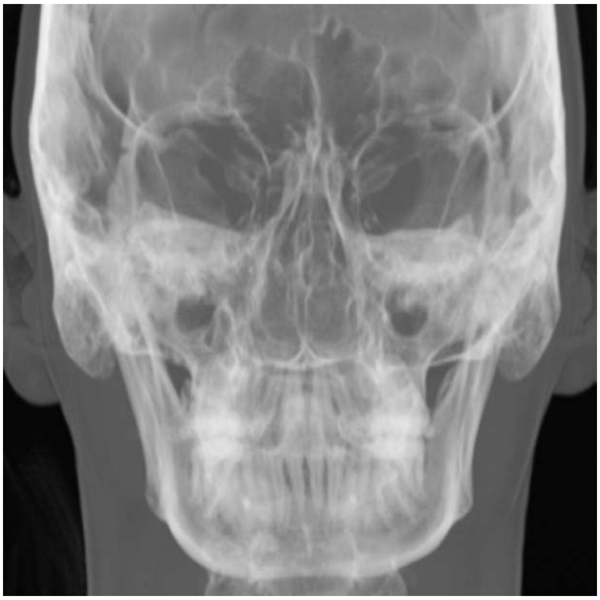

Fig 3. Close-up view of virtual frontal cephalogram (MS-CT).

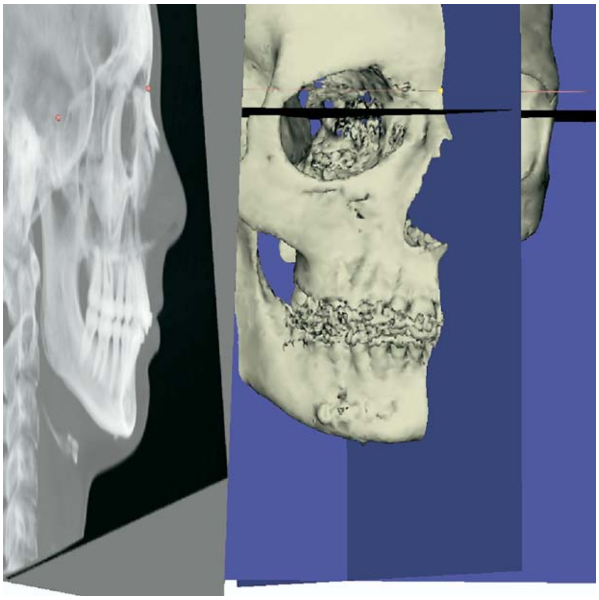

Fig 4. Virtual lateral cephalogram linked to 3D hard-tissue surface representation with superimposition of anatomic Cartesian 3D cephalometric reference system (MS-CT).

Scanning procedure of MS-CT 3D cephalometry

CT images are currently scanned according to a strict protocol. The patient must be positioned carefully in the MS-CT scanner. The occlusal plane should coincide with the axial slices to minimize the number of slices that are affected by streak artifacts caused by radiopaque dental restorations (eg, amalgam). If the patient can lie still during the CT scan, no fixation bandages should be used to avoid extra soft-tissue deformations. The patient should be checked to ensure that his mouth is closed with normal natural occlusion. The imaging parameters should be determined with a

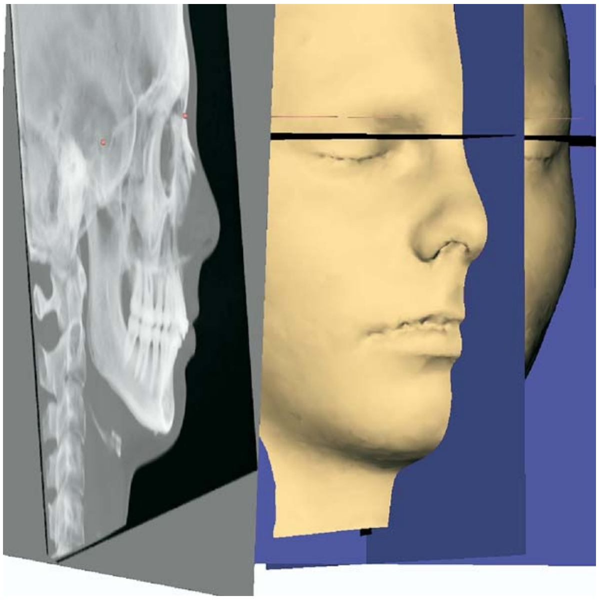

Fig 5. Virtual lateral cephalogram linked to 3D soft-tissue surface representation with superimposition of anatomic Cartesian 3D cephalometric reference system (MS-CT).

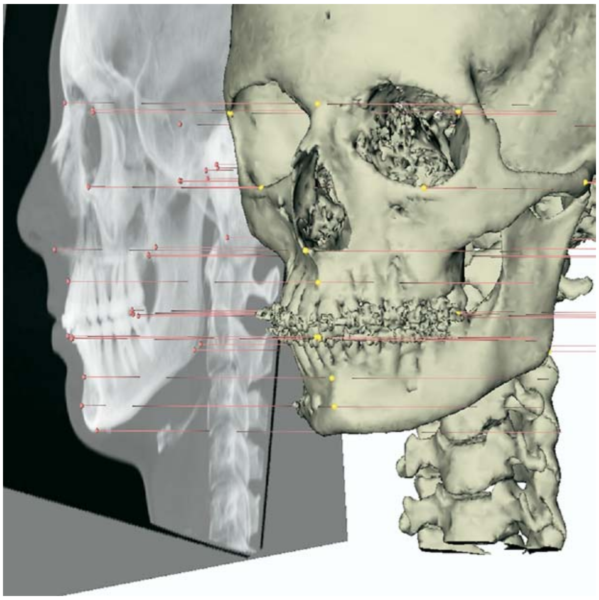

Fig 6. Virtual lateral cephalogram linked to 3D hard-tissue surface representation with setup of 3D cephalometric hard-tissue landmarks (MS-CT).

minimal dose without causing excessive noise. For MS-CT scanners, tube voltage of 120 kV and current of 80 to 90 mAs are often sufficient. The pitch (feed per rotation/total slice collimation) is preferably lower than 1 (eg, 0.75). For the reconstruction, a bone kernel is applied, and the reconstruction interval is ideally half of the detector width. A reconstruction interval of 0.75 mm is acceptable for 3D cephalometry.

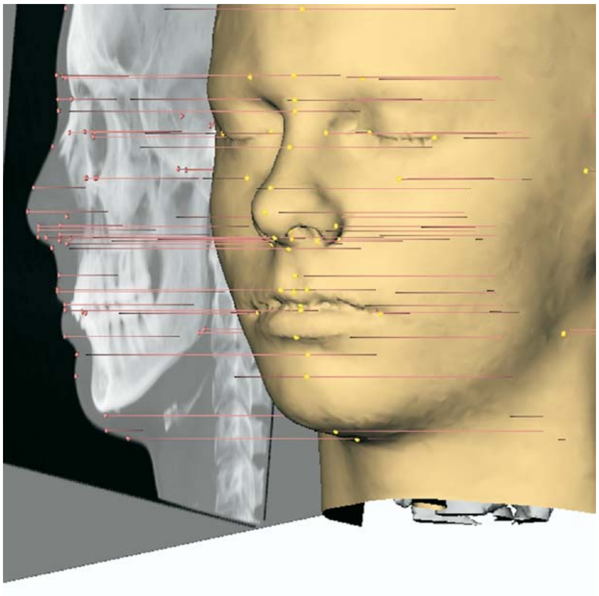

Fig 7. Virtual lateral cephalogram linked to 3D soft-tissue surface representation with setup of 3D cephalometric soft-tissue landmarks (MS-CT).

Table I. Step-by-step 3D virtual approach to MS-CT 3D cephalometry of hard and soft tissues

Step 1	Rendering of DICOM data into 3D viewer	Automated
Step 2	Standardized virtual positioning of skull	Semiautomated
Step 3	Computing and linking of virtual lateral and frontal cephalograms to 3D hard- and soft-tissue surface representations	Automated
Step 4	3D definition of nasion (N) and sella (S) landmarks	Manual
Step 5	Setup of 3D anterior cranial base (S-N) plane	Automated
Step 6	Setup of 3D anatomic Cartesian cephalometric reference system	Automated
Step 7	Definition of 3D cephalometric hard- and soft-tissue landmarks	Manual
Step 8	Definition of 3D cephalometric planes	Automated
Step 9	3D cephalometric hard- and soft-tissue analysis	Automated

Accuracy and reliability of MS-CT 3-D cephalometry

Statistical analysis showed that MS-CT 3D cephalometry is highly accurate and reliable.[2,5] Intraobserver

Table II. Effective radiation doses of various craniofacial imaging acquisition systems

Acquisition	*Effective dose*	*Equivalent natural background radiation*
CT full skull	0.93 mSv	97 days
CT mandible, maxilla, eyes	0.41 mSv	50 days
CT mandible, maxilla	0.31 mSv	38 days
CT dental mandible	0.27 mSv	33 days
CT dental maxilla	0.21 mSv	26 days
CBCT*	0.05 mSv	6 days
Cephalogram†	0.03 mSv	4 days
OPG†	0.03 mSv	4 days

*NewTom 9000 CBCT.

†Schutyser and Van Cleynenbreugel[15] originally mentioned effective dose of 0.1 mSv for conventional cephalogram and 0.05 mSv for orthopantomography based on data reported by Suetens in *Fundamentals of Medical Imaging* (http://www.cambridge.org/catalogue/catalogue.asp?isbn=0521803624). Dose reduction by direct cephalometric radiography results in effective radiation dose of 0.03 mSv in clinical practice. Also, for orthopantomography, digital imaging results in effective radiation dose of 0.03 mSv in clinical practice.

mSv, Millisievert (average equivalent dose from natural sources is estimated at about 3 mSv per year in US); *OPG,* orthopantomography.

measurement errors were low: 0.88, 0.76, and 0.84 mm for horizontal, vertical, and transverse orthogonal measurements, respectively. Interobserver measurement error was also low: 0.78, 0.86, and 1.26 mm for horizontal, vertical, and transverse orthogonal measurements, respectively. Squared correlation coefficients showed high intraobserver and interobserver reliability.

Advantages and disadvantages of MS-CT 3D cephalometry

MS-CT 3D cephalometry is a powerful craniofacial measurement tool with several advantages: (1) truly volumetric 3D depiction of hard and soft tissues of the skull, (2) real-size (1:1 scale) and real-time 3D cephalometric analysis, (3) no superimposition of anatomic structures, (4) high accuracy and reliability, and (5) the setup of a biological meaningful 3D cephalometric reference system for cross-sectional and longitudinal analysis of craniofacial changes. Although MS-CT 3D cephalometry is a major improvement over conventional cephalometry, data acquisition still has some drawbacks: (1) horizontal positioning of the patient during record taking falsifies the position of the soft-tissue facial mask, (2) lack of a detailed occlusion due to artifacts, (3) limited access for the routine craniofacial patient because of higher cost, and (4) higher radiation exposure than other craniofacial x-ray acquisition systems. Table II gives an overview of the radiation doses of various craniofacial imaging acquisition systems and shows the equivalent time to receive the same dose as natural background radiation.[15]

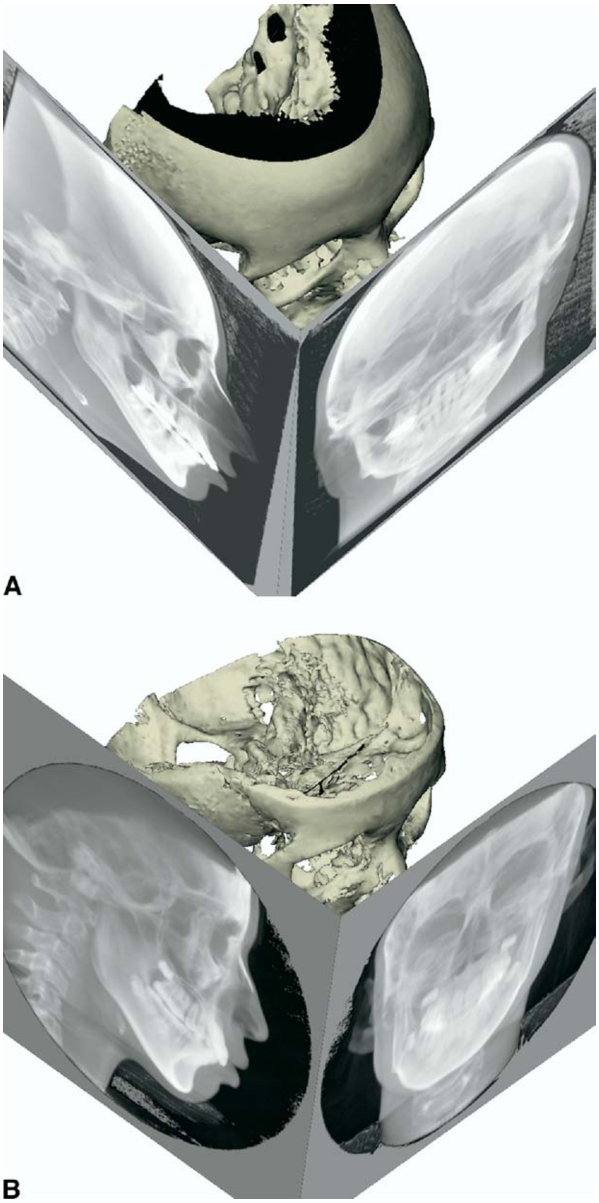

Fig 8. Virtual lateral and frontal cephalograms linked to 3D hard-tissue surface representation of skull: **A,** i-CAT and **B,** Hitachi CBCT.

The potential of CBCT 3D cephalometry

The application of CBCT technology allowed the development of a new generation of commercial volumetric dentofacial imaging acquisition systems such as NewTom (9000, 3G) (QR srl, Verona, Italy; http://www.qrverona.it), 3D Accuitomo (J. Morita, Kyoto, Japan;

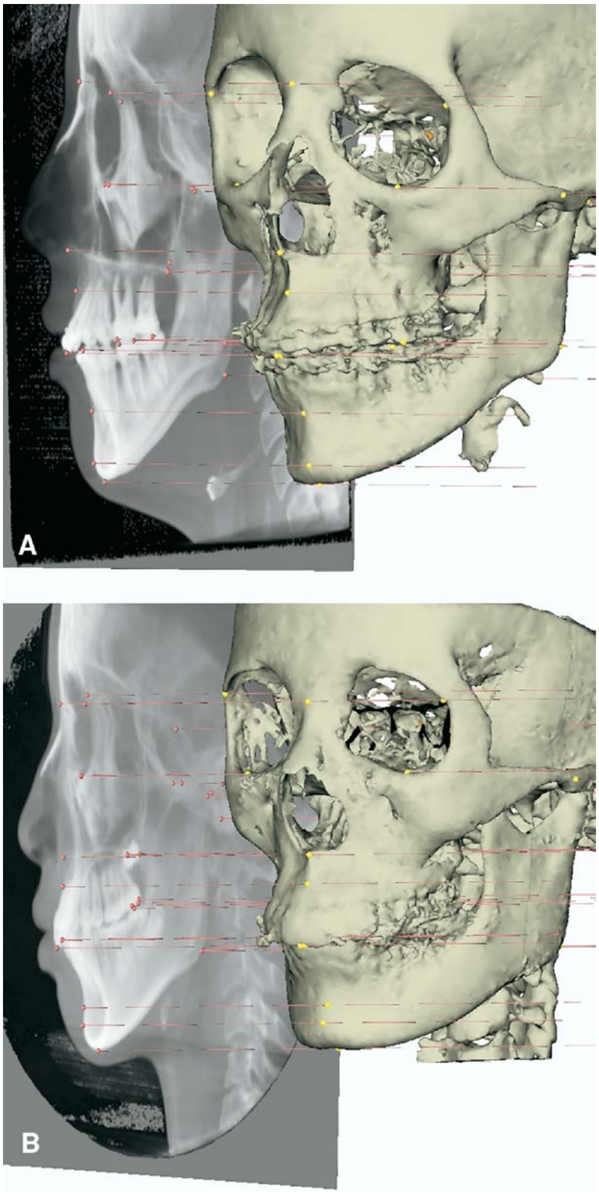

Fig 9. Virtual lateral cephalograms linked to 3D hard-tissue surface representations with setup of 3D cephalometric hard-tissue landmarks: **A,** i-CAT and **B,** Hitachi CBCT.

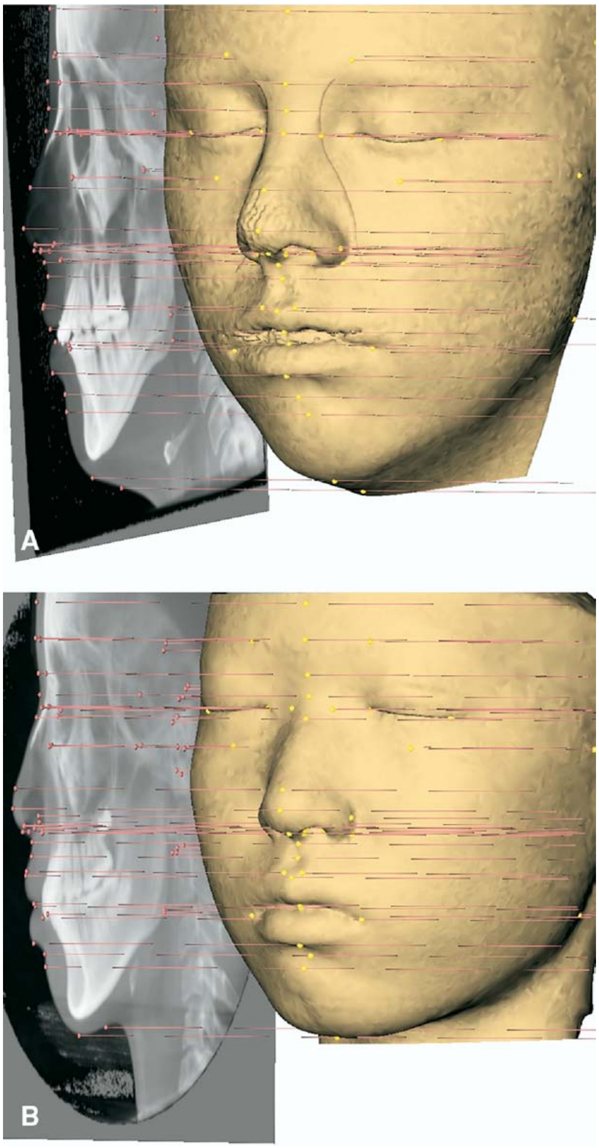

Fig 10. Virtual lateral cephalograms linked to 3D soft-tissue surface representations with setup of 3D cephalometric soft-tissue landmarks: **A,** i-CAT and **B,** Hitachi CBCT.

http://www.jmorita-mfg.com), iCAT (Imaging Sciences International, Hatfield, Pa; http://www.imagingsciences.com), and CB Mercuray (Hitachi Medical Corporation, Osaka, Japan; http://www.hitachi-medical.co.jp, http://www.hitachimed.com). CBCT scanners have a 2-dimensional detector that allows imaging of a large part of the skull with only a 360° rotational sequence. With dedicated CB reconstruction algorithms,[16] a detailed CT data volume is obtained. Similar to MS-CT, CBCT images are stored by using DICOM 3.0 as a medical-image file format. Because the focus of these CT devices is on bone imaging, the radiation dose could significantly be reduced (Table II).

CBCT 3D cephalometry, therefore, has some interesting advantages for the future: (1) reduced radiation exposure,[16,17-20] (2) natural shape of the soft-tissue facial mask because of the vertical scanning procedure (iCAT, CB Mercuray), (3) reduced artifacts at the level of the occlusion, (4) increased access for the routine dentofacial patient because of in-office imaging (sufficiently compact

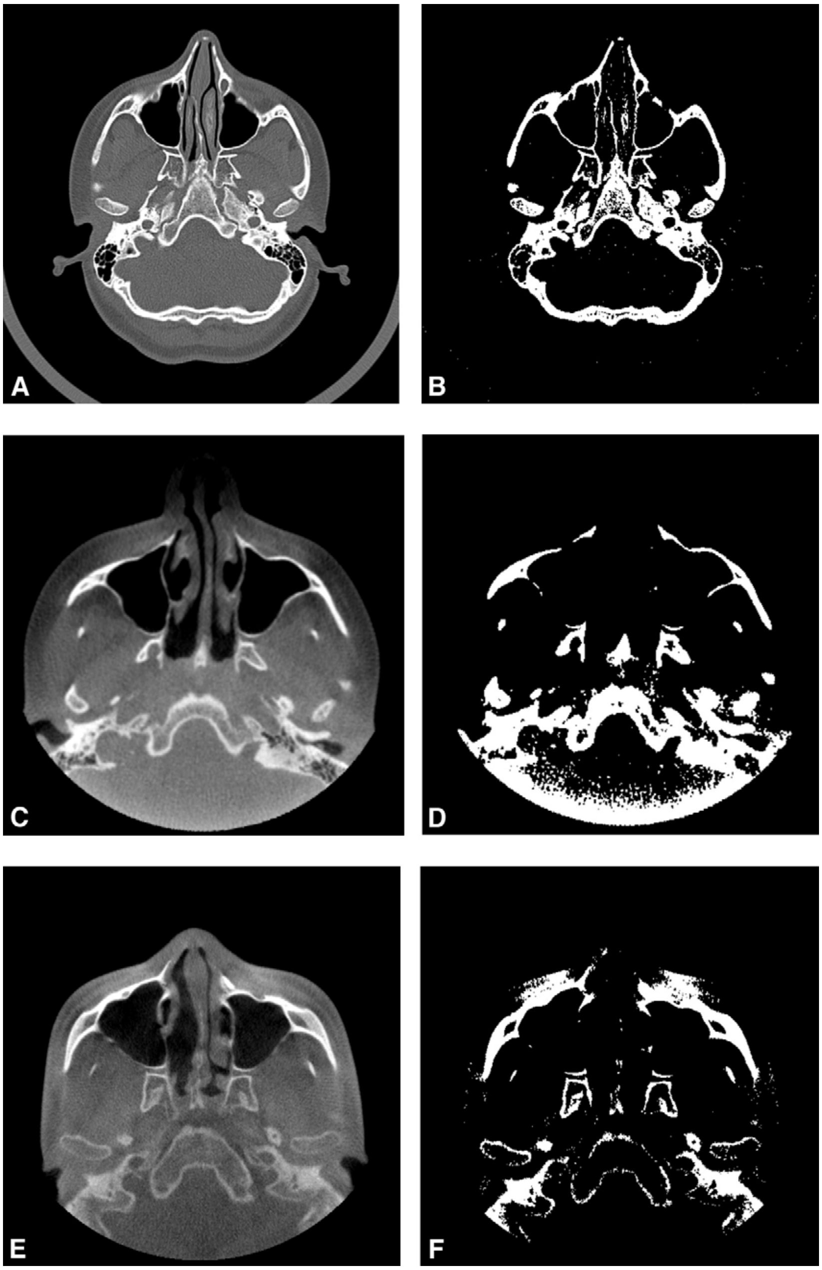

Fig 11. With MS CT imaging: **A,** image values are related to radio density in a consistent way. **B,** When image values higher than specific threshold are selected, bone is visualized. Currently, this is not the case for CBCT. With i-CAT (**C** and **D**) and Hitachi (**E** and **F**) CBCT, there is a variation in image values.

to be installed in orthodontic and oral surgery outpatient clinics and private practices), and (5) reduced costs.

The current limitations of CBCT 3D cephalometry are the scanning volume and positional dependency of the image value of a structure in the field of view of the scanner. The NewTom 3G, iCAT, and CB Mercuray CBCT scanners currently have a scanned volume that is largely sufficient for the setup of the anatomic Cartesian 3D cephalometric reference system and 3D cephalometric hard- and soft-tissue analyses (Figs 8-10) that do not involve the calvarium or complete ears. The 3D Accuitomo and NewTom9000 CBCT systems have scanning volumes that are too small and are therefore not suitable for this 3D cephalometry method.

With CBCT, the image value of a voxel of an organ depends on the position in the image volume (Fig 11). This means that the x-ray attenuation of CBCT acquisition systems currently produces different HU values (radiographic densities) for similar bony and soft-tissues structures in different areas of the scanned volume (eg, dense bone has a specific image value at the level of menton, but the same bone has a significantly different image value at the level of the cranial base). Vannier[13] stated that, when new developments in the synthesis and optimization of CBCT reconstruction algorithms allow fully exploiting the potential of area detectors in CBCT, CBCT will provide important benefits for craniofacial imaging. Hence, it is expected that improvements in both CB reconstruction algorithms and postprocessing will solve or reduce this problem soon. When this is achieved, intraobserver and interobserver accuracy and reliability of CBCT 3D cephalometry of hard and soft tissues must be analyzed.

CONCLUSIONS

This method of MS-CT 3D cephalometry is a bridge between conventional cephalometry and modern craniofacial imaging techniques and provides 3D high quality, accurate, and reliable quantitative data. It is expected that CBCT 3D cephalometry will soon enable routine craniofacial patient care because of reduced radiation exposure, accessibility, and favorable cost-benefit analysis.

We thank Dr Ryuzo Kanomi (Kanomi Dental Clinic, Himeji, Japan) for the CB Mercuray image data and Ed Marandola and Arun Singh (Imaging Sciences International, Hatfield, Pa) for the iCAT image data.

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