Clinical Applications of Cone-Beam Computed Tomography in Dental Practice

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SOMMAIRE

Les systèmes de tomodensitométrie à faisceau conique ont été conçus pour offrir une visualisation des tissus durs de la région maxillofaciale. La tomodensitométrie à faisceau conique permet d'obtenir des images de résolution inframillimétrique d'une grande qualité diagnostique, et ce en un court temps de balayage (10 à 70 secondes) et à des doses de rayonnement qui seraient jusqu'à 15 fois inférieures à celles produites par les tomodensitogrammes classiques. Grâce à la disponibilité croissante de cette technologie, le dentiste dispose d'un système d'imagerie capable de fournir une représentation tridimensionnelle du squelette maxillofacial, avec un minimum de distorsion. Cet article présente un aperçu des systèmes de tomodensitométrie à faisceau conique actuellement disponibles pour l'examen de la région maxillofaciale et passe en revue les applications précises des différents modes de visualisation de ces systèmes en dentisterie clinique.

Mots clés MeSH : radiography, dental/instrumentation; tomography, x-ray computed/instrumentation; tomography, x-ray computed/methods

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Radiology is important in the diagnostic assessment of the dental patient and guidelines for the selection of appropriate radiographic procedures for patients suspected of having dental and maxillofacial disease are available.[1] The American Academy of Oral and Maxillofacial Radiology (AAOMR) has established "parameters of care" providing rationales for image selection for diagnosis, treatment planning and follow-up of patients with conditions affecting the oral maxillofacial region, including temporomandibular joint (TMJ) dysfunction (Parameter 2), diseases of the jaws (Parameter 3) and dental implant planning (Parameter 4).[2] Although combinations of plain x-ray transmission projections and panoramic radiography can be adequate in a number of clinical situations, radiographic assessment may sometimes be facilitated by multiplanar images including computed tomographs.

For most dental practitioners, the use of advanced imaging has been limited because of cost, availability and radiation dose considerations; however, the introduction of cone-beam computed tomography (CBCT) for the maxillofacial region provides opportunities for dental practitioners to request multiplanar imaging. Most dental practitioners are familiar with the thin-slice images produced in the axial plane by conventional helical fan-beam CT. CBCT allows the creation in "real time" of images not only in the axial plane but also 2-dimensional (2D) images in the coronal, sagittal and even oblique or curved image planes — a process referred to as multiplanar reformation (MPR). In addition, CBCT data are amenable to reformation in a volume, rather than a slice, providing 3-dimensional (3D) information. The purpose of this article is to provide an overview of the unique image display capabilities of maxillofacial CBCT systems and to illustrate specific applications in clinical practice.

Types of CT Scanners

Computed tomography can be divided into 2 categories based on acquisition x-ray beam geometry; namely: fan beam and cone beam (**Fig. 1**).

In fan-beam scanners, an x-ray source and solid-state detector are mounted on a rotating gantry (**Fig. 1a**). Data are acquired using a narrow fan-shaped x-ray beam transmitted through the patient. The patient is imaged slice-by-slice, usually in the axial plane, and interpretation of the images is achieved by stacking the slices to obtain multiple 2D representations. The linear array of detector elements used in conventional helical fan-beam CT scanners is actually a multi-detector array. This configuration allows multi-detector CT (MDCT) scanners to acquire up to 64 slices simultaneously, considerably reducing the scanning time compared with single-slice systems and allowing generation of 3D images at substantially lower doses of radiation than single detector fan-beam CT arrays.[3]

Cone-Beam CT Technology

CBCT scanners are based on volumetric tomography, using a 2D extended digital array providing an area detector. This is combined with a 3D x-ray beam (**Fig. 1b**). The cone-beam technique involves a single 360° scan in which the x-ray source and a reciprocating area detector synchronously move around the patient's head, which is stabilized with a head holder. At certain degree intervals, single projection images, known as "basis" images, are acquired. These are similar to lateral cephalometric radiographic images, each slightly offset from one another. This series of basis projection images is referred to as the projection data. Software programs incorporating sophisticated algorithms including back-filtered projection are applied to these image data to generate a 3D volumetric data set, which can be used to provide primary reconstruction images in 3 orthogonal planes (axial, sagittal and coronal).

Although the CBCT principle has been in use for almost 2 decades, only recently — with the development of inexpensive x-ray tubes, high-quality detector systems and powerful personal computers — have affordable systems become commercially available. Beginning with the NewTom QR DVT 9000 (Quantitative Radiology s.r.l., Verona, Italy)[4] introduced in April 2001, other systems include CB MercuRay (Hitachi Medical Corp., Kashiwa-shi, Chiba-ken, Japan), 3D Accuitomo – XYZ Slice View Tomograph (J. Morita Mfg Corp., Kyoto, Japan) and i-CAT (Xoran Technologies, Ann Arbor, Mich., and Imaging Sciences International, Hatfield, PA).

These units can be categorized according to their x-ray detection system.[5,6] Most CBCT units for maxillofacial applications use an image intensifier tube (IIT)–charge-coupled device. Recently a system employing a flat panel imager (FPI) was released (i-CAT).[7,8] The FPI consists of a cesium iodide scintillator applied to a thin film transistor made of amorphous silicon. Images produced with an IIT generally result in more noise than images from an FPI and also need to be preprocessed to reduce geometric distortions inherent in the detector configuration.[5,6]

Advantages of CBCT

CBCT is well suited for imaging the craniofacial area. It provides clear images of highly contrasted structures and is extremely useful for evaluating bone.[8,9] Although limitations currently exist in the use of this technology for soft-tissue imaging, efforts are being directed toward the development of techniques and software algorithms to improve signal-to-noise ratio and increase contrast.

The use of CBCT technology in clinical practice provides a number of potential advantages for maxillofacial imaging compared with conventional CT:

- ***X-ray beam limitation:*** Reducing the size of the irradiated area by collimation of the primary x-ray beam to the area of interest minimizes the radiation dose. Most CBCT units can be adjusted to scan small regions for specific diagnostic tasks. Others are capable of scanning the entire craniofacial complex when necessary.
- ***Image accuracy:*** The volumetric data set comprises a 3D block of smaller cuboid structures, known as voxels, each representing a specific degree of x-ray absorption. The size of these voxels determines the resolution of the image. In conventional CT, the voxels are anisotropic — rectangular cubes where the longest dimension of the voxel is the axial slice thickness and is determined by slice pitch, a function of gantry motion. Although CT voxel surfaces can be as small as 0.625 mm square, their depth is usually in the order of 1–2 mm. All CBCT units provide voxel resolutions that are isotropic — equal in all 3 dimensions. This produces sub-millimetre resolution (often exceeding the highest grade multi-slice CT) ranging from 0.4 mm to as low as 0.125 mm (Accuitomo).
- ***Rapid scan time:*** Because CBCT acquires all basis images in a single rotation, scan time is rapid (10–70 seconds) and comparable with that of medical spiral MDCT systems. Although faster scanning time usually means fewer basis images from which to reconstruct the volumetric data set, motion artifacts due to subject movement are reduced.
- ***Dose reduction:*** Published reports indicate that the effective dose of radiation (average range 36.9–50.3 microsievert [µSv])[10–14] is significantly reduced by up to 98% compared with "conventional" fan-beam CT systems (average range for mandible 1,320–3,324 µSv; average range for maxilla 1,031–1,420 µSv).[10,11,15–17] This reduces the effective patient dose to approximately that of a film-based periapical survey of the dentition (13–100 µSv)[18–20] or 4–15 times that of a single panoramic radiograph (2.9–11 µSv).[14,17–20]
- ***Display modes unique to maxillofacial imaging:*** Access and interaction with medical CT data are not possible as workstations are required. Although such data can be "converted" and imported into proprietary programs for use on personal computers (e.g., Sim/Plant, Materialise, Leuven, Belgium), this process is expensive and requires an intermediary stage that can extend the diagnostic phase. Reconstruction

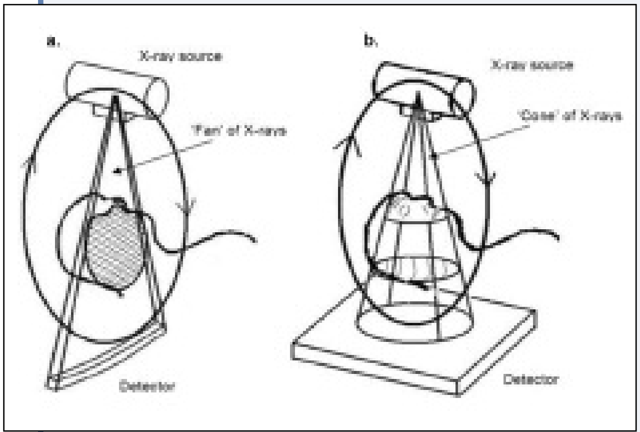

Figure 1: X-ray beam projection scheme comparing a single detector array fan-beam CT (a) and cone-beam CT (b) geometry.

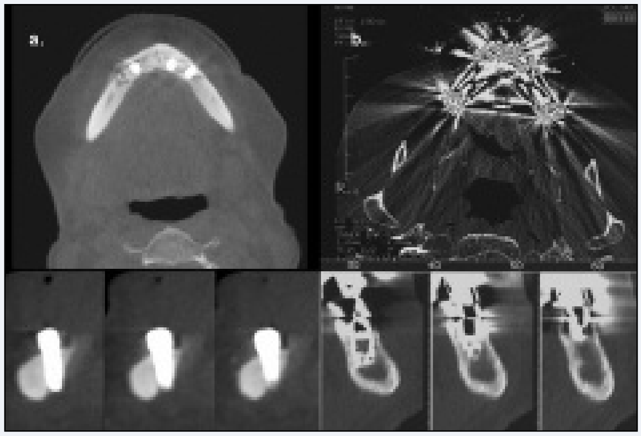

Figure 2: Relative image artifact reduction with CBCT (a) axial (top) and cross-sectional images (lower) of the mandibular arch with implants compared with conventional CT (b) axial (top) and cross-sectional (lower) images of maxillary arch with implants.

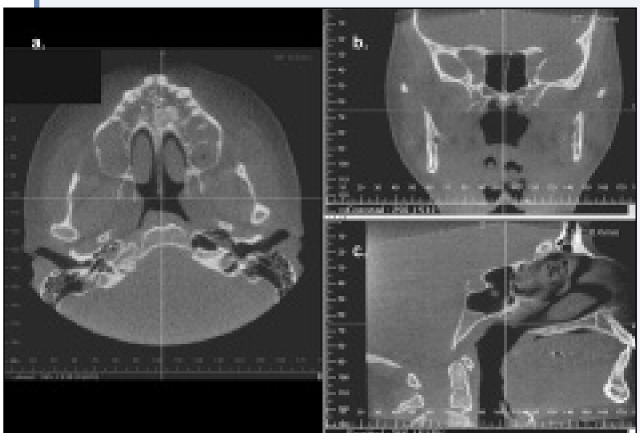

Figure 3: Representative standard CBCT monitor display (i-CAT) showing axial (a), coronal (b) and sagittal (c) thin-section slices.

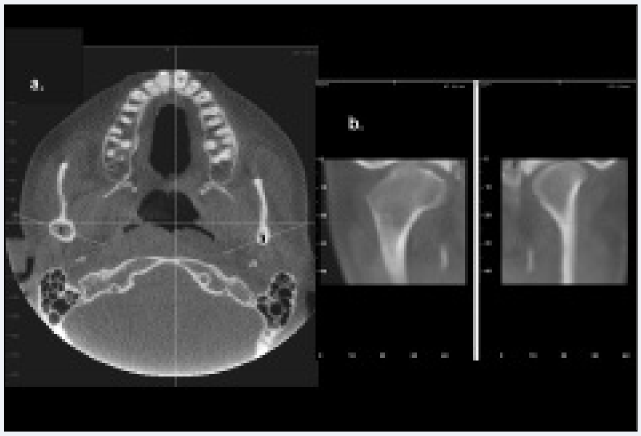

Figure 4: Bilateral linear oblique multiplanar reformation through lateral and medial poles of the mandibular condyle on the axial image (a) providing corrected coronal, limited field-of-view, thin-slice temporomandibular views (b) demonstrating right condylar hyperplasia.

of CBCT data is performed natively by a personal computer. In addition, software can be made available to the user, not just the radiologist, either via direct purchase or innovative "per use" licence from various vendors (e.g., Imaging Sciences International). This provides the clinician with the opportunity to use chair-side image display, real-time analysis and MPR modes that are task specific. Because the CBCT volumetric data set is isotropic, the entire volume can be reoriented so that the patient's anatomic features are realigned. In addition, cursor-driven measurement algorithms allow the clinician to do real-time dimensional assessment.

- *Reduced image artifact:* With manufacturers' artifact suppression algorithms and increasing number of projections, our clinical experience has shown that CBCT images can result in a low level of metal artifact, particularly in secondary reconstructions designed for viewing the teeth and jaws (**Fig. 2**).[10]

Application of CBCT Imaging to Clinical Dental Practice

Unlike conventional CT scanners, which are large and expensive to purchase and maintain, CBCT is suited for use in clinical dental practice where cost and dose considerations are important, space is often at a premium and scanning requirements are limited to the head.

All CBCT units initially provide correlated axial, coronal and sagittal perpendicular MPR images (**Fig. 3**). Basic enhancements include zoom or magnification and visual adjustments to narrow the range of displayed grey-scales (window) and contrast level within this window, the capability to add annotation and cursor-driven measurement. The value of CBCT

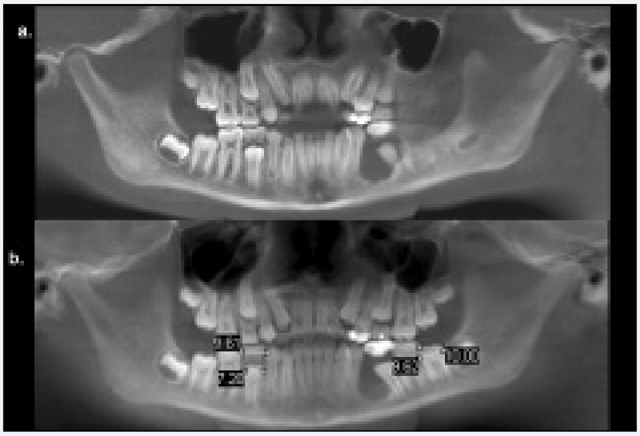

Figure 5: Narrow (5.3 mm) (a) and wide (25.6 mm) (b) slice simulated panoramic images providing anatomically accurate measurements.

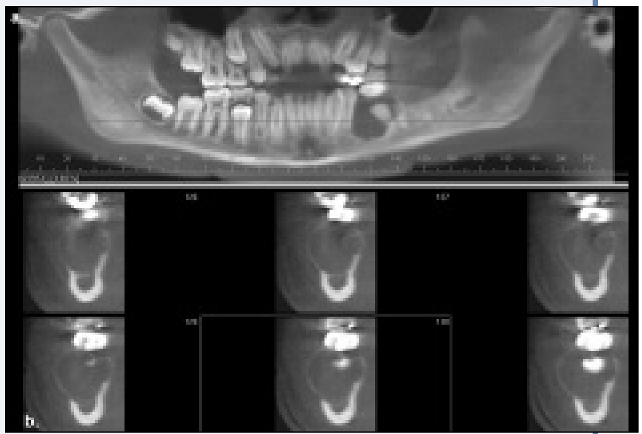

Figure 6: Reformatted panoramic image (a) providing reference for multiple narrow trans-axial thin cross-sectional slices (b) of radiolucent bony pathology in the left mandible, demonstrating bucco-lingual expansion and location of the inferior alveolar canal.

Figure 7: "Ray sum" simulated lateral cephalometric projection.

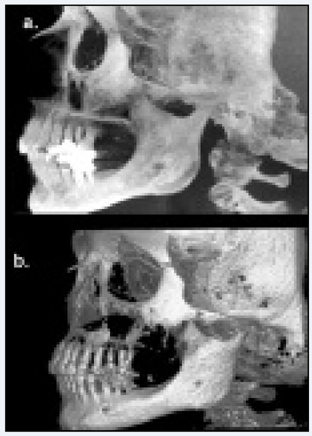

Figure 8: Right lateral maximum intensity projection (a) and shaded surface rendering of patient. (Courtesy: Arun Singh, Imaging Sciences International)

imaging in implant planning,[21–23] surgical assessment of pathology, TMJ assessment[24–26] and pre- and postoperative assessment of craniofacial fractures has been reported.[8,9,12] In orthodontics, CBCT imaging is useful in the assessment of growth and development[8,27–29] and such imaging is becoming commonplace in certain regions, especially on the west coast of the United States.

Perhaps the greatest practical advantage of CBCT in maxillofacial imaging is the ability it provides to interact with the data and generate images replicating those commonly used in clinical practice. All proprietary software is capable of various real-time advanced image display techniques, easily derived from the volumetric data set. These techniques and their specific clinical applications include:

- ***Oblique planar reformation:*** This technique creates nonaxial 2D images by transecting a set or "stack" of axial images. This mode is particularly useful for evaluating specific structures (e.g., TMJ, impacted third molars) as certain features may not be readily apparent on perpendicular MPR images (**Fig. 4**).
- ***Curved planar reformation:*** This is a type of MPR accomplished by aligning the long axis of the imaging plane with a specific anatomic structure. This mode is useful in displaying the dental arch, providing familiar panorama-like thin-slice images (**Fig. 5a**). Images are undistorted so that measurements and angulations made from them have minimal error.
- ***Serial transplanar reformation:*** This technique produces a series of stacked sequential cross-sectional images orthogonal to the oblique or curved planar reformation. Images are usually thin slices (e.g., 1 mm thick) of known separation (e.g., 1 mm apart). Resultant images are useful in the assessment of specific morphologic features such as alveolar bone height and width for implant site assessment, the inferior alveolar canal in

relation to impacted mandibular molars, condylar surface and shape in the symptomatic TMJ or evaluation of pathological conditions affecting the jaws (**Fig. 6**).

- ***Multiplanar volume reformations:*** Any multiplanar image can be "thickened" by increasing the number of adjacent voxels included in the slice. This creates an image that represents a specific volume of the patient. The simplest technique is adding the absorption values of adjacent voxels, to produce a "ray sum" image. This mode can be used to generate simulated panoramic images by increasing the slice thickness of curved planar reformatted images along the dental arch to 25–30 mm, comparable to the in-focus image layer of panoramic radiographs (**Fig. 5b**). Alternatively, plain projection images such as lateral cephalometric images (**Fig. 7**) can be created from full thickness (130–150 mm) perpendicular MPR images. In this case, such images can be exported and analyzed using third-party proprietary cephalometric software. Unlike conventional radiographs, these ray sum images are without magnification and are undistorted.

Another thickening technique is maximum intensity projection (MIP). MIP images are achieved by displaying only the highest voxel value within a particular thickness. This mode produces a "pseudo" 3D structure and is particularly useful in representing the surface morphology of the maxillofacial region (**Fig. 8a**). More complicated shaded surface displays and volume rendering algorithms can be applied to the entire thickness of the volumetric data set to provide 3D reconstruction and presentation of data that can be interactively enhanced (**Fig. 8b**).

Discussion

There is little doubt that cone-beam technology will become an important tool in dental and maxillofacial imaging over the next decade or 2. Clinical applications of CBCT are rapidly being applied to dental practice. However, although CBCT allows images to be displayed in a variety of formats, the interpretation of the volumetric data set, particularly when it comprises large areas, involves more than the generation of 3D representations or application of clinical protocols providing specific images. Interpretation demands an understanding of the spatial relations of bony anatomic elements and extended pathologic knowledge of various maxillofacial structures. Currently, any dental practitioner can purchase and operate a CBCT unit. There is mounting concern among oral and maxillofacial radiologists, based on issues of quality and patient safety, that interpretation of extended field of view diagnostic imaging studies using CBCT should not be performed by dentists with inadequate training and experience. The AAOMR has indicated that, to use CT in implant imaging, the interpreting practitioner should either be a board-certified oral and maxillofacial radiologist or a dentist with adequate training and experience.[2] Perhaps, as has occurred in medical imaging where the use and costs of imaging have increased at double-digit rates, third-party payers and federal policymakers will also become involved in setting standards for providers who bill the government for obtaining and interpreting diagnostic images.[30] Non-radiologist dentists should not be excluded from performing CBCT imaging provided they have appropriate and documented training and experience. Given that a single CBCT scan uses ionizing radiation at levels exceeding any current dental imaging protocol series, it is timely to recommend the development of rigorous training standards in maxillofacial CBCT imaging in the interests of our patients who deserve to have imaging performed by competent clinicians.

Conclusions

The development and rapid commercialization of CBCT technology dedicated to imaging the maxillofacial region will undoubtedly increase dental practitioner access to 3D radiographic assessments in clinical dental practice. CBCT imaging provides clinicians with sub-millimetre spatial resolution images of high diagnostic quality with relatively short scanning times (10–70 seconds) and a reported radiation dose equivalent to that needed for 4 to 15 panoramic radiographs. ♦

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