Fundamentals of cone beam computed tomography for a prosthodontist

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Abstract

Cone beam computed tomography (CBCT, also referred to as C-arm computed tomography [CT], cone beam volume CT, or flat panel CT) is a medical imaging technique of X-ray CT where the X-rays are divergent, forming a cone.[1] CBCT systems have been designed for imaging hard tissues of the maxillofacial region. CBCT is capable of providing sub-millimeter resolution in images of high diagnostic quality, with short scanning times (10–70 s) and radiation dosages reportedly up to 15–100 times lower than those of conventional CT scans. Increasing availability of this technology provides the dental clinician with an imaging modality capable of providing a three-dimensional representation of the maxillofacial skeleton with minimal distortion. The aim of this article is to sensitize the Prosthodontist to CBCT technology, provide an overview of currently available maxillofacial CBCT systems and review the specific application of various CBCT display modes to clinical Prosthodontic practice. A MEDLINE search for relevant articles in this specific area of interest was conducted. The selected articles were critically reviewed and the data acquired were systematically compiled.

Key Words: Artefact reduction, cone beam computed tomography, dose reduction, fundamentals, imaging accuracy, prosthodontics

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INTRODUCTION

Radiology is important in the diagnostic assessment of the dental patient and guidelines for its appropriate selection are available.[1,2] Cone beam radiographic technology was first introduced in the European market in 1996. In 2013, Tacconi, Mozzo, Godi and Ronca received an award for this revolutionary invention in maxillofacial radiology.

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The American Academy of Oral and Maxillofacial Radiology has established "parameters for care," providing the rationale for image selection for diagnosis, treatment planning and follow-up of patients including temporomandibular joint (TMJ) dysfunction (parameter 2), diseases of the jaws (parameter 3) and dental implant planning (parameter 4).[1,3]

BACKGROUND

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 (CTs). For most specialty practitioners, the use of advanced CT imaging has been limited by the cost, its availability and radiation dose considerations. However, the introduction of cone beam computed tomography (CBCT) for the maxillofacial region provides a new opportunity to request for multiplanar imaging. Most prosthodontists are familiar with the thin-slice images produced in the axial plane by conventional helical fan beam CTs. CBCT allows the creation of "real-time" images not only in the axial plane but also two-dimensional (2D) images in the coronal, sagittal and even oblique or curved image planes – a process referred to as multiplanar reformatting (MPR). In addition, CBCT data are amenable to reformation in volume, rather than a slice, providing three-dimensional (3D) information. The purpose of this article is to sensitize the prosthodontist to CBCT technology, provide an overview of the unique image display capabilities of currently available maxillofacial CBCT systems and to illustrate the specific application of various CBCT display modes to clinical prosthodontic practice.

TYPES OF COMPUTED TOMOGRAPHY SCANNERS

Computed tomography can be divided into two categories based on the acquisition of X-ray beam geometry, namely, fan beam, and cone beam.

Fan Beam Computed Tomography Technology

In fan beam scanners, an X-ray source and solid-state detector are mounted on a rotating gantry [Figure 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 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.[4]

Cone Beam Computed Tomography Technology

Cone beam computed tomography 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 [Figure 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, 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 three orthogonal planes (axial, sagittal and coronal).

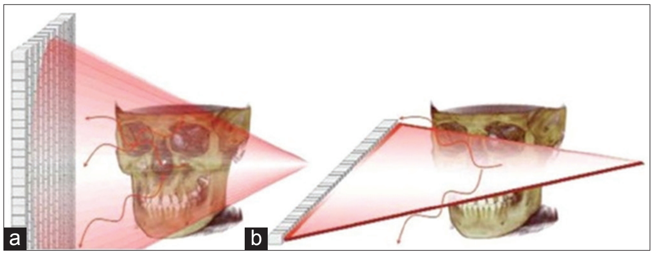

Figure 1: X-ray beam projection scheme comparing single detector array fan-beam computed tomography (a) and cone beam (b) (Courtesy: Scarfe WC, Farman AG (2007) cone beam computed tomography: A paradigm shift for clinical dentistry. Australasian Dental Practice July/August; page number 102)

Although the CBCT principle has been in use for almost two decades, only recently with the development of inexpensive X-ray tubes, high-quality detector systems like flat panel detectors (FPDs) and powerful personal computers, have affordable systems become commercially available. Beginning with the initial quantitative radiology (QR) DVT 9000 (QR s.r.l., Verona, Italy)[5] introduced in April 2001 to NewTom's latest VGi (or 5G) or other systems that include Galileos/Orthophos XG-3D (Sirona Dental company, Germany), CS9000 (Kodak Dental Systems, Carestream Health, Rochester, NY, USA), i-CAT (Xoran Technologies, Ann Arbor, Michigan and Imaging Sciences International, Hatfield, PA) and ProMax 3D max (Planmeca, Finland).

These units can be categorized according to their X-ray detection systems.[6,7] Most CBCT units for maxillofacial applications use an image intensifier tube (IIT). A system employing a flat panel imager (FPI) was released by i-CAT.[6,7] The FPI–charge coupled device, currently known as FPD, 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 FPD and also need to be preprocessed to reduce geometric distortions inherent in the detector configuration.[8,9] Hence, most of the currently available CBCT machinery is made with FPD receptors.

ADVANTAGES OF CONE BEAM COMPUTED TOMOGRAPHY

Cone beam computed tomography is well suited for imaging the craniofacial area. It provides clear images of highly contrasted structures and is extremely useful for evaluating bone.[9,10] 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, which include:

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 [Figure 2]. 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^2, their depth is usually in the order of 1–2 mm. All CBCT units provide voxel resolutions that are isotropic, that is, equal in all 3D. This produces sub-millimeter resolution (often exceeding the highest grade multi-slice CT) ranging from 0.4 mm to as low as 0.125 mm (Accuitomo; i-Cat; ProMax).

Rapid scan time

Because CBCT acquires all basis images in a single rotation, scan time is rapid (10–70 s) and comparable with that of medical spiral CT 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 of 36.9–50.3 millisievert (usv)[11-15] is significantly reduced by up to 98% compared with "conventional" fan beam CT systems (average range for mandible is 1320–3324 usv; average range for maxilla is 1031–1420 usv).[11,12,16-18] This reduces the effective patient dose to approximately that of a film-based periapical survey of the dentition (13–100 usv)[19-21] or 4–15 times that of a single panoramic radiograph (2.9–11 usv).[15,18-21]

Display modes unique to maxillofacial imaging

Access and interaction with medical CT data are not possible as workstations are required. Though this data can be "converted" and imported into proprietary programs for use of personal computers (e.g. SimPlant, Materialise, Leuven, Belgium), the process is expensive and requires an intermediary stage that can extend the diagnostic phase. Reconstruction 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" license 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 [Figure 3]. This very quality allows

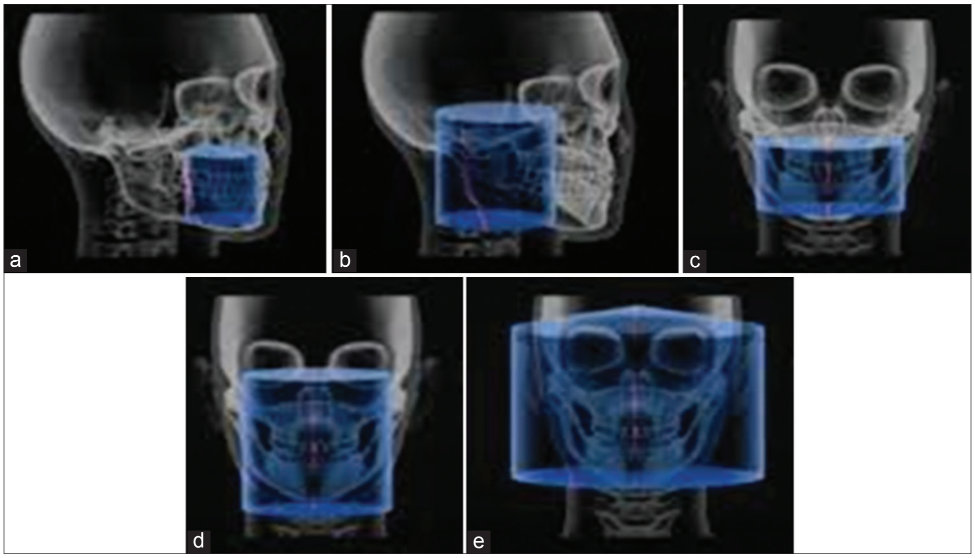

Figure 2: Volume sizes – 5 × 5" (a), 8 × 8" (b), 8 × 10" (c), 15 × 12" (d), 15 × 15" (e) used in cone beam computed tomography imaging

Figure 3: Representative standard cone beam computed tomography monitor display of Galaxis software (Sirona) showing panoramic image (a), three-dimensional image (b), tangential (c), cross-sectional (d) and axial (e)

for the software to incorporate nerve tracking with selected nerve sizes (mandibular canal, incisive canal).

Reduced image artifact

With the manufacturer's artifact suppression algorithms and increasing number of projections, clinical experience has shown that CBCT images can result in a low level of metal artifacts e.g. Metal artifact reduction software (MARS) by Sirona, particularly in secondary reconstructions designed for viewing the teeth and jaws.[11]

APPLICATION OF CONE BEAM COMPUTED TOMOGRAPHY 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. Basic enhancements include zoom or magnification, visual adjustments to narrow the range of displayed grey-scales (window) and contrast level within this window, and the capability to add annotation and cursor-driven measurements. The value of CBCT imaging in implant planning,[22-24] surgical assessment of pathology, TMJ assessment[25-27] and pre- and post-operative assessment of craniofacial fractures has been reported. In orthodontics, CBCT imaging is useful in the assessment of growth and development.[9,28-30] 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.

Cone beam computed tomography display techniques with 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, winding angles of the mandibular canal) as certain features may not be readily apparent on perpendicular MPR images.

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 (e.g. for implant planning). Images are undistorted, and hence that measurements and angulations made from them have a minimal error.

Serial trans-planar 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. I mm thick) of known separation (e.g. I 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.

Multiplanar volume reformation

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. Alternatively, plain projections images such as lateral cephalometric images 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 a 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. More complicated shaded surface displays and volume rendering algorithms can be applied to the entire thickness of the volumetric dataset to provide 3D reconstruction and presentation of data that can be interactively enhanced.

DISCUSSION

There is little doubt that cone beam technology will become an important tool in dental and maxillofacial imaging over the next decade or two. Clinical applications of CBCT are rapidly being applied to dental practice. 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. The applications in Prosthodontics include TMJ assessment, identifying dystrophic calcifications, seeking out of impacted teeth, implant planning which cannot do without the CBCT, especially with the new MARS and nerve tracking capabilities that it possesses. Integrating the CBCT images with the computer aided design-computer aided manufacturing interface has led to the development of precision fabrication of surgical stents, thereby making giant strides in proper implant placement.

Further, it may help in developing protocols to understand the ideal occlusion and the physiologic rest position in lieu of the multiplanar 3D reformatted images of the teeth and TMJ. Once the software for the soft tissue imaging achieves a better signal-noise ratio, Prosthodontists would have a very strong armamentarium for the comprehensive rehabilitation of patients.

CONCLUSION

The development and rapid commercialization of CBCT technology dedicated to imaging the maxillofacial region will undoubtedly increase the Prosthodontist's access to 3D radiographic assessment in clinical practice. CBCT imaging provides the clinician with sub-millimeter spatial resolution images of high diagnostic quality with relatively short scan times (10–70 s) and a reported radiation dose equivalent to that needed for just 4–15 panoramic radiographs.

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