REVIEW ARTICLE

Two Dimensional versus Three Dimensional Imaging in Dentistry: An Updated Review

Gour Sundar Bhowmick

Post Graduate Student, Department of Oral Medicine and Radiology, Vyas Dental College and Hospital, Jodhpur, Rajasthan, India

ABSTRACT

Radiographic imaging is a preliminary and a very essential step in the diagnosis, treatment planning, and follow-up of all the cases in dentistry. The interpretation of an image can be influenced by several confounding factors including the regional anatomy and superimposition of both teeth and the surrounding dentoalveolar structures. Due to the complexity of the maxillofacial skeleton, conventional two dimensional (2D) radiographic images fail to provide accurate information of the particular region of interest. Superimposition of the images, seen in planar periapical radiography, reveal only limited information about a three dimensional (3D) object. The structures so visualized are also subject to geometric distortion. Hence, recent research has highlighted the need for 3D imaging modality to overcome the potential drawbacks of conventional radiography. Medical computed tomography (CT) was one of the earliest 3D imaging systems. It has been used in the field of dentistry over the past decade but with limited success. This can be ascribed to high radiation exposure, lengthy scan time and cost factor. The next new phase in imaging modalities came with the advent of cone beam CT (CBCT). Contemporary dentistry emphasizes on the significance of CBCT since it limits the radiation exposure and rapidly provides 3D reconstructed images which have been proven to be accurate in all aspects. This paper reviews the importance of 3D CBCT technology over conventional 2D imaging system along with its potential drawbacks.

Key words: Computed tomography, Cone beam computed tomography, Dental radiography, Diagnostic imaging

INTRODUCTION

Diagnostic imaging is considered as an important adjunct in clinical assessment of the patient. Since time immemorial, radiology has played a key role in dentistry and now with expanding array of different imaging modalities and it has become an indispensable tool in dental assessment as well. The first intraoral radiograph to be used in dentistry was reported by Sir C Edmond Kells.[1] Thereafter, the field of radiology has seen several changes. With improvements in the film technology and reduced exposure times, gradually film based system gave way to advanced sensor-based digital systems. Solid state sensors such as charge coupled device, complementary metal oxide semiconductor, and photostimulable phosphor plates largely replaced the film based conventional imaging.[2-4] Digital systems also provided opportunities for image processing and modification (color, brightness, and contrast) which further assisted the diagnostic process. But the images were still a two dimensional (2D) representation of three dimensional (3D) anatomy and the need for cross-sectional information was still unmet.

Need for 3D Visualization

The principle of working of an intraoral radiography system is based on the transmission, attenuation, and recording of X-rays on a film or digital receptor. It requires optimized geometric configuration of the X-ray machine, object, and sensor to provide an accurate projection. If any one of the components of the imaging system is compromised, the resulting image obtained may have errors in geometry or distortion. The image produced by a conventional periapical radiograph is a 2D representation of a 3D area of interest and possess inherent limitations of magnification, distortion, and superimposition.[5] These constraints paved way for the advanced techniques of cross-sectional imaging which revolutionized the concept of diagnosis and treatment planning in dentistry.[6,7]

Corresponding Author: Dr. Gour Sundar Bhowmick, Department of Oral Medicine and Radiology, Vyas Dental College and Hospital, Jodhpur, Rajasthan, India. Phone: +91-8100489003. E-mail: gour_abu@rediffmail.com

EVOLUTION OF CONE BEAM COMPUTED TOMOGRAPHY (CBCT) SYSTEM

CT was invented in 1972 by British engineer Godfrey Hounsfield of EMI Laboratories, England, and by South Africa-born physicist Allan Cormack of Tufts University, Massachusetts. In 1990, Tachibana and Matsumoto first reported the application of this technology in dentals. The dental CT also known as DentaScan (GE Healthcare) was first reported by Schwarz *et al*.[8] A CT scan utilizes a narrow fan-shaped beam of X-ray radiation and multiple exposures around an object to display 3D images in the form of image slices. It was a revolutionary step in diagnosis and treatment as it helped the clinician to assess the morphologic features, pathology and outcome assessment in all the 3D perspectives. Although they produced precise images compared to 2D radiography, the high radiation dose, expensive scanner units and lengthy scanning time of these systems limited their popularity. Furthermore, the tomographic data captured in medical CT machine was in the form of anisotropic voxels which made the measurements made in multiple planes inaccurate. Hence, keeping in mind the dictum of "as low as reasonably achievable" (ALARA) newer 3D scanning machines were developed.[9] In 1998, Mozzo *et al*. introduced a new volumetric CT machine (CBCT) that used the cone beam technology for maxillofacial imaging. The first CBCT unit which was approved by the Food and Drug Administration (FDA) in the United States in march 2001 was known by the name New Tom Digital Volume Tomography (DVT) 9000 (Quantitative radiology srl, Verona, Italy). Later, other units such as 3D Accuitomo (J. Morita, Kyoto, Japan), i-CAT (Imaging Sciences Int, Hatfield, PA), CB Mercury (Hitachi Med Corp, Chiba-ken, Japan), Galileos (Sirona Dental Systems LLC, Charlotte, NC), Scanora 3D (SOREDEX, Milwaukee, WI), and Kodak 9500 (Kodak Dental Systems, Rochester, NY) were the various other FDA approved CBCT units manufactured in succession and used in dental practice. At present, CBCT is considered as a complementary imaging modality for specific applications rather than a replacement for the conventional imaging system.[10,11]

CBCT or DVT utilizes a cone-shaped X-ray beam which is centered on a 2D detector. It performs a single rotation around the object of interest and then captures a series of 160-599 basis images. During the rotational exposure, the X-ray source emits radiation and several sequential planar images of the field of view (FOV) are obtained in a complete or sometimes partial arc pattern. Software programs using sophisticated algorithms including back filtered projection are applied for these image data to generate a 3D volumetric data set. These can be used to provide the primary reconstruction images in the axial, sagittal, and coronal planes (Figures 1 and 2). The unit measurements for 2D imaging are called as pixels. However, in CBCT, the captured image consists of voxels

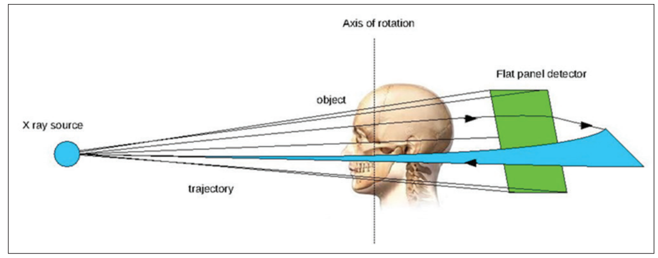

Figure 1: Schematic representation of the working mechanism of a cone beam computed tomography scan unit

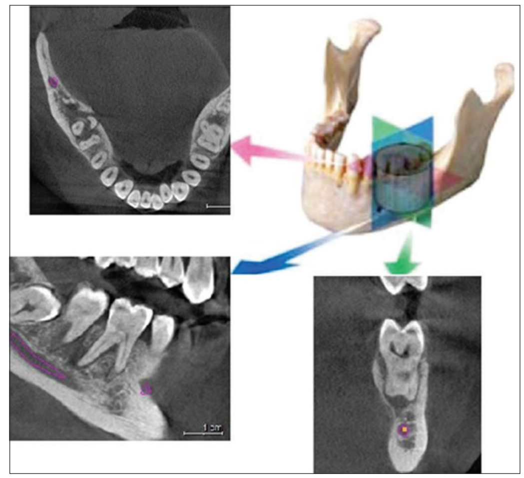

Figure 2: Standard display modes of cone beam computed tomography volumetric data in the axial, sagittal, and coronal plane

(3D representation of pixels). CBCT was found to be better than medical CT since it offered significant scan time reduction, reduced radiation dosage and reduced cost for the patient. It requires lesser electrical energy than the fan-shaped beam technology. In CBCT, the entire data are obtained in a course of a single sweep of the scanner and it captures a cylindrical or spherical volume of data known as FOV. Unlike CT scanners, CBCT voxels are isotropic that is equal in all dimensions. This is useful for recording precise measurements of the area of interest. Subjective image quality of CBCT is also high compared to helical CT for the highest resolution modalities.[12,13]

Types of CBCT

The most common classification of CBCT is based on the dimensions of their FOV or scan volume. The following categorization has been proposed.

Small volume (also referred to as focused, limited volume) systems possess a maximum scan volume height of 5 cm. Single arch CBCT scans have a FOV height of 5-7 cm within a single arch; inter-arch CBCT scans have a FOV height of 7-10 cm; maxillofacial CBCT scans have a FOV height which is in the range from 10 to 15 cm; craniofacial CBCT have a FOV height in excess of 15 cm. If the region of interest encompasses the entire jaw portion or entire viscerocranium, a larger FOV scanning unit should be used. Thus, they are useful in the diagnosis and treatment planning of orthodontic cases, temporomandibular joint analysis, maxillofacial trauma imaging, and pathologies involving the jaws. However, if only a small area needs to be imaged involving one or more teeth, a smaller FOV may be used using limited CBCT units. They are mostly appropriate for dentoalveolar imaging and in dental s. Another difference between limited and full CBCT units is that a voxel unit is generally smaller for the limited CBCT unit (0.1-0.2 vs. 0.3-0.4 mm) hence it offers higher resolution helpful for dental applications.[14]

The other methods of classifying CBCT systems are based on the patient position during the scan (supine, sitting, or standing) or functionality of the systems (standalone or hybrid multimodal systems). Multimodal units are those units which combine digital panoramic and/or cephalometric radiography with a small to medium FOV CBCT system. The main advantage of combining the functions is that these units reduce the overall office footprint for imaging equipment and are less expensive than standalone units, as existing robotic panoramic platforms can be re-engineered using small, cost-effective detectors.[15]

Exposure

The CBCT units are manufactured with fixed exposure settings or can also be manually adjusted in relation to the peak kilovoltage (kVp) and/or milliamperage (mA). The operators who use CBCT units with exposure settings which can be adjusted should realize that these parameters directly influence both image quality and patient radiation dose. Therefore, careful selection is required to fulfill the ALARA or as low as practical principles.[16,17] The adjustment should be done based on the size of the patient and should be according to the manufacturer's recommendations. While mA may be increased to compensate for an increase in patient size, the ratio of patient effective dose increases proportionately in the order of 1:1. Adjustment of kVp has an even greater effect on dose than does mA, hence reducing kVp to approximately 20% decreases the radiation dose by nearly 40%, provided all the other parameters remain the same.[18]

Resolution

There are two types of image resolution–spatial resolution and contrast resolution. Spatial resolution is the ability to show fine details, such as demonstrating the periodontal ligament space or a narrow root canal. Most of the CBCT devices allow choice of this setting. Depending on the type of CBCT unit, lower resolution may be chosen resulting in reduced patient radiation dose.[19] Contrast resolution is the ability to discriminate between the different types of tissues with very minor differences in X-ray absorption, and the differences are displayed in gray levels. Numerous factors limit the contrast resolution of CBCT which includes noise, the resolving capacity of flat-panel detector, refinement of projection geometry, the display characteristics of the monitor, and inherent discriminatory limitations of the human eye. Higher image resolution is obtained by higher radiation dosage which is definitely harmful to the patient. Hence, it is important to reduce the exposure parameters to avoid unnecessary exposure of the patient and the clinician to the harmful radiation. Hence, the clinicians who are operating the CBCT must have a thorough understanding of the operational settings and their effects on the quality of the image and radiation safety.[20,21]

Radiation Dosage

When X-ray radiation exposures are evaluated, the measure of effective dose (E) or radiation is expressed in Sieverts. The values of E are calculated based on the relative tissue compositions within the FOV and how sensitive they are to radiation.[14] International Commission on Radiological Protection in 2007 published new factor values for specific organs and tissues while calculating the effective radiation doses. The effective dose calculation for head region imaging includes the skin, bone surface, bone marrow, thyroid, esophagus, salivary glands, brain, and the "other" tissues. The effective dose of CBCT units are comparable to panoramic radiography and few intraoral radiographs but are much lesser compared to the multislice CT machine (Table 1).[22,23] The effective dose of CBCT is affected by the FOV size, sensitivity of the digital detector, exposure beam type, electric potential power in the X-ray tube, beam geometry, and number of rotations around the object to be imaged. However, it should be remembered that the basic principles of ALARA should always be effectively followed to avoid excess radiation exposure.[24,25]

Softwares of CBCT

There is a number of software's available with each type of CBCT unit. These are Sidexis 4, CS 3D, Planmeca Romexis 3D, Sicat Suite, i-dixel 3D imaging software. They give high-resolution volumetric image from a small, medium or large FOV to provide an immediate overview of the

Table 1: Comparison of effective radiation dosage among the various imaging modalities

Imaging modality	Effective dose (μSv)
Intra-oral (film or digital) radiograph - (1)	<8.3
Dental bite-wing radiographs (F-speed) - (4)	38
Full mouth series radiographs	35-388
Panoramic radiograph	9-26
Cephalometric radiograph	2-6
CBCT (dentoalveolar-small and medium FOV)	4.7-38.3
CBCT (craniofacial-large FOV)	68-1073
Medical CT (head)	2000

CBCT: Cone beam computed tomography, FOV: Field of view anatomy such as maxillary sinus cavity, inferior alveolar nerve, and the thickness of bone before detection of any pathology or implant placement. The images can be instantly viewed from different projections or converted into numerous cross-sectional slices. Measuring and annotation tools such as mandibular nerve canal tracing assist in safe and accurate treatment planning for implant placement. It also serves as an excellent patient education tool as shown in Figure 3.

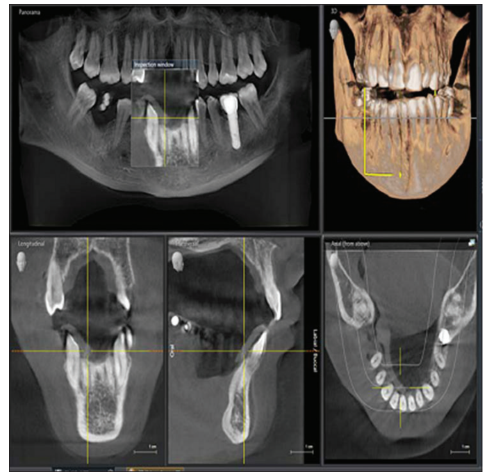

Figure 3: Targeted display and editing of a three dimensional (3D) data volume and its cross sectional views visualized by the cone beam computed tomography software (CS-3D)

Recent Advancements

The most recent advancement is the development of Tx STUDIO 5.4 software inbuilt in i-CAT CBCT technology. With the help of Tx Studio 5.4 3D software, placing and restoring implants, performing guided surgery, and treatment of complex dental cases have been extremely easy (Figures 4 and 5). The rich visual images help in educating and motivating the patient to accept the proposed treatment plan. A significantly more efficient and productive office with the fastest 3D radiographic workflow is available and chairside case workups can be completed in minutes with greater precision and lesser radiation dosage (Figures 4 and 5).

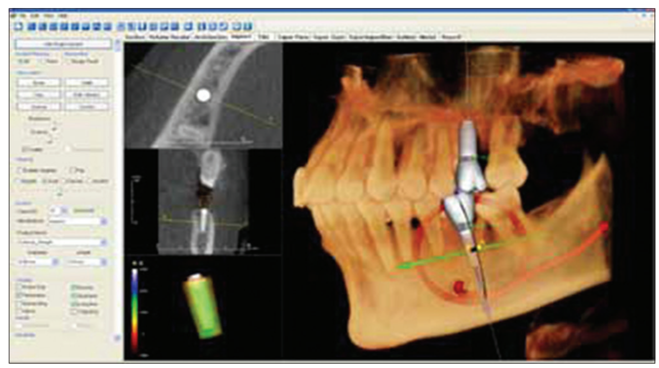

Figure 4: Evaluation of bone density in various panes of view before planning for implant placement using Tx Studio (5.4) software

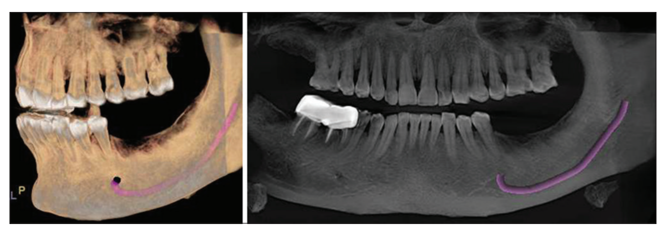

Figure 5: Three dimensional (3D) views to visualize the inferior alveolar nerve position during presurgical planning for placement of implant by CS-3D software

Advantages of 3D CBCT Imaging Over 2D Imaging

The introduction of CBCT technology in clinical dental practice has provided many advantages for maxillofacial imaging. They are as follows.

Analysis of root canal morphology

CBCT was found to be a very reliable and non-invasive method to view root canal anatomy in all the spatial planes (axial, coronal, and sagittal) and eliminates the risk of image distortion and anatomic noise.[26-28] The accuracy of CBCT and other imaging modalities in the identification of the root canal morphology has been evaluated and compared to the modified canal staining and clearing technique by Neelakantan *et al.* CBCT was found to correctly identify all the root canals in almost 99.71% of the cases. It could correctly identify the presence of the second MB2 canal in all cases in maxillary molars which were commonly missed out by periapical radiographs. It was found by various studies that the CBCT detection rates increased from 60% to 93.3% with increasing resolution suggesting that if CBCT has to be used, then resolutions in the order of 0.12 mm or less are optimal.[29,30] CBCT can be used along with dental operating microscope for identification of the internal anatomy of maxillary first molar.[31] They can also be used to assess teeth with unusual morphology such as "C-"shaped canals, dilacerated teeth, dens in dente fused teeth, or teeth with unusual number of roots.[32-34]

Assessment of root canal preparations and intraoperative procedures

Periapical radiographs give only 2D limited information about a 3D root canal system. CBCT has been very effective non-invasive method for the measurement of root dentin thickness, canal curvature, and canal centering by providing images in orthogonal as well as oblique planes. Thus, CBCT images permit nondestructive and metrically exact analysis of variables such as volume, surface area, cross-sectional shape, and taper of the canal. They are also useful during intraoperative procedures such as detecting missed canals during retreatment, broken instruments, perforations, and calcified canals.[35,36]

Detection of periradicular lesions

For a lesion to be visible on a periapical radiography, minimum of 30-50% of bone loss should be present.

Lesions within the cancellous bone generally cannot be detected by conventional 2D radiography unless there is extensive destruction of the bone cortex on the outer surface, or there is erosion of the cortical bone from the inner surface. CBCT can reveal bone defects present in the cancellous and cortical bone separately even at the earliest stages of the pathological event. This was mostly because there was no superimposition of the cortical bone over the lesion by elimination of anatomic noise.[37] Estrela *et al*.[38] demonstrated the higher prevalence of apical periodontitis diagnosed by CBCT imaging compared to conventional radiography. Thus, early diagnosis of periradicular radiolucent changes by CBCT permitted the clinician to early identify and modify their treatment plan thereby giving a positive treatment outcome. In asymptomatic apical periodontitis, CBCT was much more sensitive in detecting the existing periapical radiolucency which routine radiographic examinations failed to diagnose.[39] They were also useful in detection of lesions close to the maxillary sinus, sinus membrane thickening, and when there was less than 1 mm bone present between the lesion and floor of maxillary sinus in cases of posterior teeth.[40] CBCT was also useful in cases of diagnostic dilemma where benign and malignant lesions like carcinoma and odontogenic cyst mimicked periapical lesions when viewed by radiographs alone. Thus, it provides the clinician with great detail and much information and proving the presence of any previously undiagnosed pathosis or any odontogenic etiology of pain.[41]

Diagnosis of traumatic injuries

The diagnosis of root fractures and cortical bone fractures after traumatic injuries are based on clinical findings, sensitivity tests, and radiographic examination. Horizontal root fractures are generally detected taking multiple angled periapical radiographs. However, they might not still be properly visualized in the radiographs. 3D CBCT is useful by providing high-resolution images in the three planes with no errors in geometry of the image.[42] Vertical root fractures (VRF) or longitudinal root fractures are difficult to diagnose since the clinical signs and symptoms are non-specific and can often be overlooked if the incident X-ray beam is not parallel to the plane of fracture line while taking periapical radiographs. CBCT reconstructed data provide precise information to clearly visualize the fracture line in the axial, coronal, and sagittal plane with just a single exposure. It is advantageous over medical CT since images are produced at a faster speed and lower doses of radiation.[43] Edlund *et al*.[44] evaluated the diagnostic efficacy of CBCT in suspected VRF in dental ally treated teeth using exploratory surgery and found that the positive predictive value of CBCT was 91% making it the most reliable tool in the diagnosis of VRF. In general, CBCT with a smaller FOV is more sensitive in detecting VRF than larger FOV systems.[45]

Diagnosis of root resorption and perforations

Conventional periapical radiographs provide limited clinical information with respect to the 3D defect such as root resorption. It is unable to reveal the exact location and nature of the resorptive defect or thickening of remaining root canal dentine, particularly in the buccolingual direction. There are further image distortion and superimposition of various anatomic structures resulting in limited diagnostic information. 3D CBCT reconstructed images are useful in the diagnosis of the size of the defect as well as its proximity to the root canals.[46,47] The CBCT voxels being isotropic, ensures that the images produced are completely accurate geometrically and free from distortion thus accurately differentiating between external and internal type of root resorption.[48] In addition, they are also useful in identifying the portal of entry of the periapical lesions to differentiate invasive cervical resorption from internal root resorption. CBCT imaging also allows for better visualization of the perforation site in various sections and angulations without any geometric distortion of images.[49]

Assessment of the quality of root canal treatment and outcome assessment

CBCT is used as a superior imaging modality in assessment of teeth with ideal root canal treatment and in cases where canals are filled short of the apex. CBCT was useful for accurately measuring the working length of teeth (precision varied between 0.41-0.51 mm) when compared with the electronic apex locators which are considered as the gold standard method for working length estimation. It was useful in patients with cardiac pacemakers where the use of an apex locator is contraindicated and periapical radiography is unreliable.[50,51] Periapical radiography cannot detect accurately if there is any existing periapical lesions post dental treatment. However, CBCT was useful in detecting the asymptomatic non-healed lesions during the post-treatment follow-up period to identify the cases requiring retreatment.[52]

Presurgical assessment

Conventional radiography gives limited information in the buccal-lingual plane, and the presence of the buccal plate interferes while estimating the defects in osseous structures such as periapical lesions. Distortion of images in panoramic radiographs has also been well documented and quantified, making it a challenging medium to gain accurate measurements. The use of CBCT has been recommended for dental surgery treatment planning since it enables the assessment of the lesion in 3D plane in terms of its location, extent, position of the roots within the bone, proximity to anatomic vital structures such as inferior alveolar nerve, mental foramen, maxillary sinus, and nasal cavity.[53] It also allows better visualization of the extruded dental material and its proximity to the inferior alveolar nerve and mental foramen than 2D radiography.[54] Periapical radiographs are found to be less sensitive in detecting lesions associated with the upper molar teeth since the root apices are in very close proximity to the floor of the maxillary sinus (anatomic noise). CBCT is very effective in such cases by providing 3D image without superimposition.[40] The role of CBCT in providing accurate linear measurements and 3D evaluation of the alveolar ridge with fabrication of the surgical guides is also useful during placement of implants.[55]

Disadvantages of CBCT

CBCT images also possess certain limitations such as formation of image artifacts, graininess of the image, and poor soft tissue contrast. CBCT image artifacts are mostly due to the following possible sources: The patient, the scanner, X-ray beam artifacts, and artifacts related to the CBCT system such as partial volume averaging, under sampling, and cone beam effect. The cone beam effect occurs mostly in the peripheral portions of the scan volume mostly due to the divergence of X-ray beam. As a result, less information is obtained for the peripheral structures resulting in streaking artifacts, image distortion, and greater peripheral noise. Image artifacts can also occur due to the inherent polychromatic nature of X-ray beam which is known as beam hardening. Two types of artifacts are observed due to beam hardening. They are (1) Cupping artifact is the distortion of metallic structures due to the differential absorption of X-ray beam and (2) streaks and dark bands which can be present between two dense objects.[56] Graininess of the image might be due to remaining noise occurring in the CBCT systems with large FOV mostly when a low signal is used to attempt to reduce the radiation exposure. Such artifacts can be eliminated by reducing the FOV to avoid scanning structures outside the ROI which are susceptible to beam hardening. Poor soft tissue contrast is also seen in CBCT due to many factors which include the X-ray beam being divergent in nature causing large variation or nonuniformity of the X-ray beam incident on the patient and nonuniform absorption with greater signal-to-noise ratio on the cathode aspect of image relative to the anode side. Furthermore, the flat panel detector based artifacts can affect its response to the X-ray radiation. Recent scientific reports have discussed about the increasing professional concerns over the potential association between radiation exposure and cancer.[57,58]

CONCLUSION

The advent of the 3D CBCT imaging system has provided the clinician a powerful tool to facilitate interactive image manipulation and enhancement, thus significantly increasing the amount of information gleaned from a volume. This relatively modern state-of-art imaging technology has added another dimension to dental radiography and is quickly becoming the gold standard for radiographic imaging in dentistry. Maxillofacial CBCT imaging provides very accurate, submillimeter resolution images of great diagnostic quality, enabling 3D visualization of the complex osseous structures of the maxillofacial region. In clinical dentals, the application of CBCT should be based on a benefit-risk analysis. Since CBCT utilizes ionizing radiation, patient exposure should be kept ALARA to avoid unnecessary radiation hazards. Operators of the CBCT equipment should be aware of the effects that the additional exposure settings have on both the image quality and patient radiation dose. Hence, oral health professionals have an ethical responsibility to become familiar with the technical and operational aspects of CBCT, as well as understand the scientific validity and associated health risks of its applications.

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