3D Imaging in Endodontics

A New Era in Diagnosis and Treatment

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ISBN 978-3-319-31464-8 ISBN 978-3-319-31466-2 (eBook)
DOI 10.1007/978-3-319-31466-2

Library of Congress Control Number: 2016942098

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

Preface and Acknowledgments

New radiographic imaging systems have recently become available for use in dentistry and have transformed the way we diagnose and treat oral disease. Among these new imaging technologies are medical computed tomography (CT), cone beam computed tomography (CBCT), and magnetic resonance imaging (MRI). These imaging technologies benefit from advancements in other technologies such as high-speed computer processors and sophisticated software.

The subject of this book, CBCT, allows for the precise visualization and evaluation of teeth and surrounding structures. CBCT has great potential to become an essential diagnostic and treatment planning tool in the modern endodontic practice. However, like any new technology, we need to carefully consider appropriate indications for use, to maximize patient benefit and minimize potential risk.

Chapter 1 provides a basic understanding of CBCT from an oral radiologist's perspective. This includes imaging basics, CBCT image acquisition, rendering, viewing, and manipulation.

Chapter 2 addresses utilization of CBCT in the diagnosis and management of periapical pathosis, diagnosis of pain, cracked teeth and vertical root fractures, internal and external resorptive defects, and traumatic injuries. These are all challenging diagnostic problems that are frequently encountered in clinical practice.

Chapter 3 addresses the impact of CBCT technology on endodontic nonsurgical and surgical treatment planning. This chapter will review and compare the relative value of preoperative 2D periapical radiographs and CBCT in the decision-making process.

Chapter 4 focuses on the value of CBCT in understanding tooth anatomy prior to nonsurgical and surgical root canal therapy. The primary objective of root canal therapy is the treatment and/or prevention of apical periodontitis. A successful result requires that the operator understands and appreciates the internal anatomy and morphology of the root canal system.

Chapter 5 addresses the clinical applications of CBCT in nonsurgical endodontic retreatment. This chapter will provide an overview of how to analyze cases by viewing selected fields, coupled with a 3D-rendered perspective of the jaw segment which enables the clinician to perform a "virtual analysis" of the case prior to treatment.

Chapter 6 reviews the different applications of CBCT in diagnosis, treatment planning, and long-term outcome evaluation of periradicular surgery. In this chapter, cases will be presented to demonstrate the value of CBCT in presurgical assessment, case selection, and treatment planning in endodontic microsurgery, including the use of CBCT to identify and manage teeth in close proximity to important anatomical structures.

Chapter 7 reviews the application of CBCT for detection, classification, localization, and differentiation of internal and external resorptive defects.

We would like to offer our sincere thanks to the contributors and co-authors of this book who have generously shared their time, expertise, and case materials.

Dr. Mohamed Fayad: I would like to dedicate this book to my father Dr. Ibrahim M. Fayad who was an instrumental figure in my life. I would like to thank my parents for all the guidance, support, and the opportunities they gave me to be who I am.

I would like to thank my wife Marilia and my children Nagi, Lila, and Zachary for their love and support they gave me over the years.

Brad Johnson thanks his wife, Liza, and three adult children, Jason, Chris, and Leah, for their support and encouragement over many years.

Both Mohamed and Brad would like to acknowledge and thank their fellow faculty, mentors, and students in the University of Illinois at Chicago Department of Endodontics, who have encouraged us and given us the time and resources to pursue this project.

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1 Principles of Cone Beam Computed Tomography

Sanjay M. Mallya

1.1 Introduction

Radiographic examination is an essential component of the overall endodontic diagnosis and treatment planning process. For decades, periapical and panoramic imaging has provided this radiological information. Although these imaging modalities provide valuable information, they are limited by their inherent 2-dimensional nature. Superimpositions from adjacent structures can potentially mask anatomical variations or pathological lesions. The introduction of cone beam computed tomography (CBCT) in dentistry provided us with a diagnostic tool that overcomes this basic limitation of conventional radiographic techniques. Over the last 15 years, CBCT technology has grown rapidly to allow clinicians to acquire high-resolution images of the teeth and craniofacial bones, using relatively low radiation doses. CBCT imaging has several applications in dento-maxillofacial diagnosis including endodontic diagnosis and treatment planning, implant treatment planning, surgical and orthodontic treatment planning, evaluation of the paranasal sinuses, temporomandibular joints, intraosseous pathology, impacted teeth, etc. Clinicians who use CBCT imaging should be familiar with the basic principles of CBCT image acquisition. This chapter provides the reader with basic principles of computed tomography, and the relevant hardware and software components of a CBCT system, with a focus on their impact on image quality. It discusses radiation dose considerations in using this x-ray-based imaging modality, approaches to communicate radiation risks to the patient, and methods to minimize patient radiation exposure.

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M. Fayad, B.R. Johnson (eds.), *3D Imaging in Endodontics*,
DOI 10.1007/978-3-319-31466-2_1

1.1.1 What Is Computed Tomography?

Computed tomography (CT) is a radiographic modality used to generate cross-sectional images of the body. In this technique an x-ray source and a radiation detector array rotate around the patient, sequentially making two-dimensional projections at hundreds of different angles along the rotational arc. At each angle, the projection represents a map of x-ray attenuation by objects along the path of the x-ray beam. Sophisticated mathematical algorithms are applied to this attenuation data to spatially reconstruct the locations of the structures within the imaged volume. Both multi-detector CT (MDCT), an imaging modality widely used in medicine, and dental CBCT use these basic physical and computational processes. Although MDCT and CBCT share similarities in the principles of image formation, there are important differences between these two technologies.

- In MDCT the x-ray source is collimated to a narrow fan-shaped beam. In contrast, in CBCT imaging, the radiation source is collimated to a cone or pyramidical beam that fully encompasses the region to be imaged. Due to the narrowly collimated beam in MDCT, the amount of scatter radiation that reaches the detector is lower, and thus, the contrast-to-noise ratio (CNR) of MDCT is higher than that of CBCT. Thus, MDCT provides much better contrast resolution than CBCT.
- The detectors used in CBCT enable a spatial resolution that is typically higher than that of MDCT images. Thus, CBCT is better suited for high-resolution diagnostic tasks, such as evaluation of teeth and periapical structures.
- An important difference between MDCT and CBCT is the radiation dose—typically MDCT protocols use much higher doses of radiation than that used for CBCT imaging.

1.2 CBCT Image Acquisition

Current dental CBCT units offer users with a variety of features that range from differences in design and footprint, technical specifications of the detectors, selectable fields of view (FOV), and the extent of the source-detector rotation during image acquisition. Many of these technical parameters influence the image quality as well as the radiation dose to the patient [1]. Clinicians should be familiar with these parameters to design patient-specific CBCT examinations that provide adequate diagnostic information, with the least possible radiation exposure to the patient.

1.2.1 X-Ray Source and Exposure Settings

As with all x-ray-based imaging modalities, an x-ray tube serves as the source of x-radiation. X-ray tubes used in dental CBCT units may have either stationary or rotating anodes. Most dental CBCT units will allow the operator to adjust the x-ray tube voltage (peak kilovoltage, kVp) and/or the tube current (milliamperes, mA). Similar to other radiographic techniques, the kVp and mA should ideally be adjusted for each patient, taking into account the density of the structures to be imaged and the patient's size. This is important to make a diagnostically optimal radiographic image, while minimizing the patient's radiation exposure. Some CBCT units have fixed exposure parameters that cannot be modulated by the operator. Some CBCT units, for example, the NewTom 5G unit, use an automatic exposure control mechanism that customizes the mA on a patient-specific basis. Such features provide the ability to automatically maintain low radiation dose exposure during CBCT imaging.

1.2.2 Image Detector

During the rotation of the x-ray source-detector assembly, the image detector captures x-ray photons to produce a two-dimensional x-ray transmission image or a basis projection. The basis projections acquired at the different rotational angles constitute the raw data for CT reconstruction. Most currently available dental CBCT units use a flat-panel detector (FPD). In this digital detector, a phosphor screen of gadolinium oxysulfide or cesium iodide converts x-ray photons to light photons, which are then detected using a thin-film transistor array [2]. Another detector type used in dental CBCT units is the image intensifier. In this detector system, x-rays strike a fluorescent screen to produce visible light photons, which are converted by a photocathode into electrons to amplify the initial signal [3]. The electrons are accelerated and strike an output phosphor screen to produce a visible image that is captured by a CCD camera. The assembly of these various components makes the design of an image intensifier bulky. FPD provides significant advantages over image intensifier-based units. FPD is more sensitive to x-rays. Compared with image intensifiers, FPD generates images with higher contrast resolution and spatial resolution. Another disadvantage of image intensifier-based systems is the decreasing image quality over the lifetime of the unit as the phosphor screen ages.

1.2.3 Number of Basis Projections

As described above, the first step in CBCT imaging is acquisition of two-dimensional images during rotation of the x-ray source-detector assembly around the patient. The number of basis projections acquired differs between CBCT units and depends on the frame rate, the time of rotation, and the extent of the rotational arc. In general, a CBCT scan acquired with a higher number of basis projections produces an image with a higher spatial and contrast resolution. However, with a higher number of projections, the radiation dose to the patient is higher. Many CBCT manufacturers have incorporated preset scan modes that alter the number of basis projections to either enhance image quality or lower the patient radiation dose.

1.2.3.1 Extent of the Rotation Arc (180° vs. 360°)

In many CBCT units, the basis projections are acquired during an entire 360° rotation around the patient's head. For some CBCT units, the x-ray source-detector assembly rotates around the patient for approximately 180°. In some versatile units, the operator can set the length of the rotation arc (180° vs. 360°). When a partial arc is used, fewer basis projections are acquired. This has the advantage of not only reducing the patient's radiation exposure but also decreasing scan time, thereby decreasing artifacts due to patient motion. The partial arc imaging yields a CBCT scan with lower spatial and contrast resolution [4]. However, this reduction in image quality does not always compromise the diagnostic utility of the scan. For example, the accuracy of linear measurements made for implant treatment planning is not compromised by a 180° scan mode [5]. In contrast, partial arc imaging decreases the visibility of pulp canals and increases the number of false positives when detecting vertical fractures [6]. It should be emphasized that the effect of partial arc rotation on the diagnostic efficacy is strongly dependent on the diagnostic task at hand and remains to be fully studied.

1.2.3.2 "Quick Scan" and "Fast Scan" Imaging Modes

Some CBCT units incorporate a selectable scan mode that is designed to substantially lower radiation doses. This is accomplished by requiring fewer basis projections, thereby decreasing both the scan time and the radiation dose. With these modes, the contrast-to-noise ratio is considerably lower and, thus, decreases image quality. Despite this decreased image quality, some diagnostic assessments can be adequately made, such as evaluation of root parallelism during orthodontic treatment. However, it is likely that the decreased image quality will impact certain high-resolution diagnostic tasks such as evaluation of the periodontal ligament space, root resorption, and subtle areas of bony erosion. The impact of the scan modes on the accuracy of such diagnostic tasks remains to be critically evaluated.

1.2.3.3 "High-Resolution" Scan Mode

Many CBCT units feature a selectable "high-resolution" scan mode, where the number of basis projections is increased to yield images with a higher resolution. Clinicians should use caution when using this scan mode. Importantly, such scan protocols require longer scan times and expose the patient to higher doses of radiation. The radiation exposure with this scan mode is approximately twofold higher than that in the standard scan mode. For some units the scan time with a high-resolution scan mode is as long as 40 s, thereby increasing the potential for patient motion during scan acquisition. Clinicians should be aware that a high-resolution scan mode does not always yield an image that is diagnostically superior. Standard resolution acquisitions (typically the manufacturer's default setting) are adequate

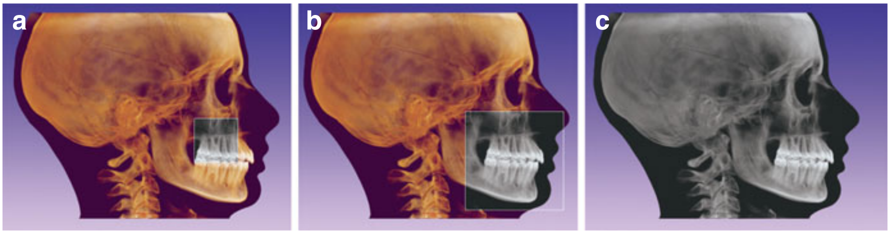

Fig. 1.1 Schematic representations of the approximate anatomical coverage provided by different fields of view of a CBCT unit. (**a**) Small FOV, (**b**) medium FOV, and (**c**) large FOV

for most diagnostic tasks and the use of a high-resolution scan mode may not add any additional diagnostically useful information.

1.2.3.4 Field of View (FOV)

The FOV is a critical parameter that must be optimized for individual CBCT imaging examinations. When selecting a specific FOV, the CBCT unit collimates the x-ray beam to a predetermined image volume size. Although there are no formal definitions, the FOV is categorized as large (maximum dimension greater than 15 cm), medium (approximately 8–15 cm), or limited/small (maximum dimension less than 8 cm diameter, Fig. 1.1). As a general rule, the smallest FOV that provides adequate anatomic coverage for the diagnostic task at hand should be selected. In some basic CBCT units, the FOV is fixed and cannot be changed by the operator. Most CBCT units are versatile, and the FOV can be selected through a range of limited to medium to full FOV coverage. Selection of the appropriate FOV is particularly important—it determines the extent of anatomic coverage and also impacts image quality and patient radiation dose. For most endodontic diagnostic tasks, a limited FOV scan will likely provide adequate anatomic coverage.

In almost all units, a smaller FOV scan is acquired using a smaller voxel size, thus yielding images with higher spatial resolution. Furthermore, a smaller FOV also reduces scattered radiation, decreasing image noise and contributing to improved image quality. This is particularly important given that many of the endodontic diagnostic applications require higher resolution, for example, evaluation of the periodontal ligament space and lamina dura. Selection of the appropriate FOV should be made considering not only the anatomic coverage but also the image resolution required for the diagnostic task. For example, in a patient with atypical odontogenic pain, all the teeth in a selected quadrant may need to be imaged to rule out an odontogenic cause for the pain. Such patients may possibly benefit from two adjacent limited FOV scans, rather than a single medium or large FOV scan. In this scenario, the lower image resolution with the medium/large FOV scan is likely to compromise critical evaluation of the apical periodontal structures.

1.2.3.5 Voxel Size

The smallest three-dimensional data unit on a CBCT image volume is the voxel. The voxel size depends on the size of the detector pixels, which in current CBCT systems ranges from 0.07 to 0.4 mm. In general, a CBCT scan acquired with a smaller pixel size produces an image with higher spatial resolution. Nevertheless, the detector pixel size is not the only determinant of image resolution. Several other machine-specific parameters such as CT reconstruction algorithms and image processing "filters" modulate the signal-to-noise ratio and image resolution.

In many CBCT units, the voxel size is predetermined for a specific FOV. Typically, smaller FOVs are imaged using a smaller pixel size. In some CBCT units, the operator can manipulate the pixel size for a given FOV. For these protocols, imaging at a smaller pixel size is accomplished by either increasing the number of basis projections or increasing the radiation exposure factors. Clinicians must be aware that these protocols will deliver a higher patient radiation exposure, compared with the standard protocol.

1.3 CBCT Artifacts

The CBCT imaging process starts by making sequential two-dimensional projections along hundreds of angles around the area of interest. Each projection represents a map of x-ray attenuation by objects along the path of the x-ray beam. Mathematical algorithms are applied to this attenuation data to spatially reconstruct the locations of the structures within the imaged volume. There are several factors that influence the accuracy of the reconstructed data. These include discretization of the imaged object, geometrical projection issues, detector noise, and the assumptions in mathematical modeling. Discrepancies between the reconstructed data and the physical state of the actual object may be evident in the image and are termed artifacts. There are several different artifacts described in CT imaging. These include beam hardening artifacts, photon starvation artifacts, cupping artifacts, and partial volume averaging. Schulze et al. [7] provide an excellent description of the physical basis for and the appearances of these various artifacts.

Beam hardening artifacts are noted around dense bony structures and around radiopaque restorations and endodontic filling materials. Clinicians who use CBCT must be aware of the appearances of such artifacts and not confuse them with pathological changes. For example, metallic restorations will result in dark bands and streaks (Figs. 1.2, 1.3, and 1.4). The dark bands which extend to the region around the restoration and to the crowns of the adjacent teeth may be interpreted as caries. When these bands appear on the crowns or roots of adjacent teeth, they may be misinterpreted as caries or root fractures. Likewise, the region around metallic posts and gutta-percha yields dark bands, which may compromise the ability to detect fractures or resorption of the adjacent root structure.

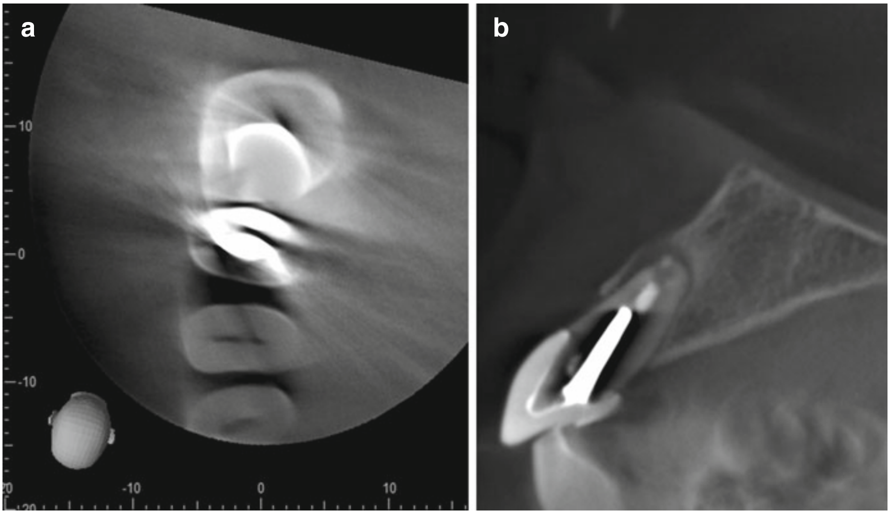

Fig. 1.2 (**a**) Axial slice demonstrating metallic restorations in the second premolar and first molar teeth. Note the radiating pattern of dark bands and streaks. Note how linear artifacts are evident on the root of the adjacent first premolar. (**b**) Sagittal CBCT section through the maxillary central incisor. Note the dark zone around the metallic post

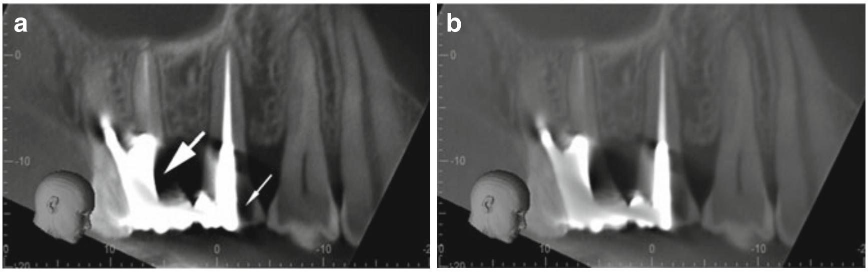

Fig. 1.3 (**a**) Sagittal slice demonstrating metallic restorations in the second premolar and first molar teeth. Note the dark bands on the molar crown (*big arrow*) and the crown of the second premolar (*small arrow*). (**b**) Same section as in panel A. Note how adjusting the density and contrast allows for better visualization of the crown and root surfaces in the regions of the dark bands, further confirming their artifactual nature

1.4 Radiation Dose Considerations

The basic premise of diagnostic radiographic imaging is that the benefits from the examination far outweigh the risks associated with ionizing radiation exposure. The principles of radiation risk and safety that apply to conventional periapical and panoramic radiography also apply to CBCT imaging. CBCT users should be familiar with the doses delivered by various CBCT imaging protocols, the risks