Craniofacial 3D Imaging

Current Concepts in Orthodontics and Oral and Maxillofacial Surgery

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We would like to dedicate this book to the many different individuals who have guided us along life's pathway, so we were able to share these developing concepts and changes with others.

There are our parents. They are Serap and Asif as well as Francis and George, who have unselfishly dedicated everything so we could be the best we can be. There are our brothers and sister who came along with us shouldering burdens and sharing joy. They are Aydin and Asli, Jeff and Barb, and Sue Ann and Dan.

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Last but not least, it has been our pleasure to help guide and direct the future members of our fine profession and specialty. Our current and past orthodontic graduate students/residents at the University of Oklahoma have given us great encouragement and a brightness that shines now and will continue in the years to come.

Cheers.

Onur Kadioglu and G. Fräns Currier

Preface

We have envisioned this textbook to be a current reference that highlights the use of 3D imaging through Cone Beam CT technology with emphasis on orthodontics and oral and maxillofacial surgery. We would like to recognize and present those areas that are impacted by 3D imaging by either changing the way one thinks about conventional orthodontic diagnosis and treatment planning or through the various types of tooth and surgical jaw movements. Our goal is to demonstrate planning and execution with emphasis on the limits of the alveolar bone, airway and temporomandibular joints. These areas of interest will be demonstrated not only by recalling the available science but also employing current translational research findings that our distinguished authors and editors have been executing in their respective disciplines, whether in departments, clinics and hospitals.

We have judiciously selected an outstanding group of authors whom we strongly believe will have a positive impact for any reader, directing their thought processes during diagnosing and treatment planning of their patients.

Oklahoma City, OK, USA

Onur Kadioglu
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Contents

Part I The Overview

Part II Diagnosis and Treatment Planning: Analyses, Airway and TMJ

Part III Clinical Applications in Oral Surgery and Orthodontics

Part I

The Overview

1

History, Technique, and Safety

Farah Masood, Onur Kadioglu,
and G. Fräns Currier

Abstract

The scope of dental imaging has been greatly expanded with the invention of cone beam computed tomography (CBCT). The everyday functionality of dental practice, especially for dental specialties like orthodontics and oral surgery, has certainly changed with this radiographic technology for treatment planning and evaluation. The discovery of X-rays was made by Wilhelm Conrad Rontgen in 1895, who was a known physicist for his work. He won a Nobel Prize in 1901 for this discovery. Ever since this revolution, constant technologic advancements have been made in the field of dental radiology that had resulted in improving the diagnostic accuracy and reducing the radiation exposure in every day dental practice. In dentistry, conventional two-dimensional (2-D) radiographic imaging has been widely used. However, the conventional radiographic images have limitations like inherent magnification, distortion, superimposition of structures, and lack of depth for three-dimensional anatomical objects. Over the years, the technology has improved tremendously in terms of image quality and radiation dose. With CBCT, the visualization of structures is possible with much clarity and without superimposition. The technology has shown a profound impact on the dental practice with its widespread applications.

1.1 Introduction

Computed tomography (CT) imaging was originally called computed axial tomography (CAT) scan. Researchers started the development of medical CT scanners in the 1960s. Later around 1970–1972, Dr. Godfrey Hounsfield (electrical engineer at EMI Central Research Laboratories, England) and another physicist Allan Cormack of Tufts University (Boston, MA) introduced the CT imaging modality for clinical applications. The Nobel Prize was awarded to both of them in 1979 for the development of computerized tomography, as the technology had a profound impact in improving the diagnostic methodology. The technology was patented by Dr. Hounsfield in 1973 [1]. In the mid-1970s, a full-body scanner was developed by a dentist-physicist Dr. Robert Ledley of Georgetown University (Washington, DC).

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To capture the data, the medical CT scanner uses an X-ray beam and image detectors, mounted and fixed on a rotating gantry, which rotates around the patient to capture the region of interest. During the rotational movement of the gantry, the X-ray beam passes through the patient, and the remnant X-ray photons remaining after the attenuation are captured by the image detectors. The “raw data” acquired by this process is reconstructed by a computer algorithm, and the end result is generation of cross-sectional images of the patient’s tissues. The process uses a series of radiographic images to create sequential images, and virtual slices of body tissues are produced.

Initially, the first-generation CT scanners acquired the data in the axial plane by “slice-by-slice” scanning with a narrow fan-shaped X-ray beam and a single array of detectors. Eventually, the development of spiral CT (1989) and the multislice image detector systems (1988) leads to the acquisition of volumetric data [2]. Modern CT scanners are much faster as they use array of multiple detectors with the rotating fan-shaped X-ray beam and capture multiple slices of data simultaneously, in a short period of time. This has resulted in shorter scan times and lesser radiation dose to the patient as well [3].

With this technique, information about the internal structures is obtained by reformatting of the data and production of cross-sectional images, and the structures are visualized without superimposition. For image display, the components of the gray images are pixel and voxels. A voxel defines a point in three dimensions, whereas the pixel defines a point in two dimensions. Pixel or picture element represents the smallest single module of an image in a two-dimensional (2-D) framework. The attenuation of X-ray photons or signal by the patient’s tissues determines the value and intensity of each individual pixel that is captured by the detector, and the information is displayed on the computer screen. Pixel size effects the image resolution. Voxel adds detail and third dimension (3-D) or depth to the image.

Medical multi-detector computed tomography (MDCT) units use Hounsfield units (HU) to display relative density values of various body structures according to a calibrated gray value scale.

For viewing, the reconstruction of data produces images in multiple imaging planes. During the CT scanning process, the data is captured in the axial or transverse plane. Axial plane is an imaginary plane that divides the structure or body into upper and lower portions. From this axial data set, the computer software programs can generate multiplanar reformatted images in axial, sagittal, and coronal planes by combining the information. The sagittal plane sections the structure or body into right and left, and the coronal plane divides the structure or body into anterior and posterior sections. Also, 3-D computer-generated models of the structures can be made. MDCT units have superior contrast resolution and can display soft tissues with more superior quality. Medical- or hospital-based CT units have large footprints and are supine gantry-style units with considerably high radiation exposure to the patient. Before the introduction of CBCT for dental needs, MDCT units were utilized for diagnosis and treatment planning for only limited cases in dentistry. Factors like lower radiation dose and ease of use in dental setting lead to the development of cone beam computed tomography.

1.2 What Is Cone Beam Computed Tomography (CBCT)?

CBCT was introduced in the early 2000s to the main market. As stated earlier, before CBCT was introduced to the main market, the conventional CT and MDCT scanners were used by the dental specialties to obtain cross-sectional views for pathology, maxillofacial trauma, and in limited number of dental implant cases. However, the utilization of MDCT was very limited due to higher radiation doses as compared to CBCT. Cost of the procedure was also very high. Many CBCT systems are available (Fig. 1.1).

Cone beam computed tomography (CT) has the potential to reduce the size and cost of CT scanners. Because this emerging technology

Fig. 1.1 Picture of currently available ProMax 3D CBCT scanner (Courtesy of Planmeca Oy, Helsinki, Finland)

produces images with isotropic submillimeter spatial resolution, it is ideally suited for dedicated dentomaxillofacial CT scanning. When combined with application-specific software tools, cone beam computed tomography can provide dentomaxillofacial practitioners with a complete solution for performing specific diagnostic and surgical tasks, such as dental implant planning.

The other terms used to describe this technology include cone beam volumetric imaging (CBVI) and cone beam volumetric tomography (CBVT).

The introduction of low-dose CBCT scanning systems has changed this approach for everyday dental practice. It is specifically designed to produce three-dimensional images of the maxillofacial region. The computer software programs are designed for dental needs.

CBCT scanners are connected to a computer, and the data or the region of interest is acquired with a single full 360° or partial rotation of the cone-shaped X-ray beam and reciprocal rotating single image detector around the patient's head. The scan times are usually less than 15–20 s. The system uses back-projection reconstruction tomographic technique. MDCT acquires image data using multiple rows of detectors, where multiple slices must be stacked to obtain a complete image [3].

The CBCT technology exposes the whole region of interest or the head of the patient with one flat-panel detector. This baseline data are then used to generate individual image slices in different planes. In CBCT image acquisition, there is no additional mechanism needed to move the patient during the scanning, and also the use of cone-shaped beam in CBCT increases the utilization of the X-ray energy by lowering the X-ray tube heat capacity required for volumetric scanning as compared to a fan-shaped beam in MDCT [4]. CBCT units have isotropic (equal in all three dimensions) voxel resolution in which images with isotropic submillimeter spatial resolution are produced [3]. Image detectors with smaller pixels tend to capture fewer X-ray photon per voxel and thus result in more noise. Higher radiation doses are required for a reasonable signal-to-noise ratio, which improves the image quality. The following factors also effect the spatial resolution and image quality: focal spot of the X-ray generator, patient-to-detector distance, X-ray source-to-patient distance, and patient movement. Smaller focal size, reduced patient-to-detector distance, and increased X-ray source-to-patient distance minimize the geometric unsharpness of the images. In practice, movement of the patient's head is a big factor that will deteriorate the image quality [4]. Many CBCT machines have artifact reduction tools that allow minimization of the noise due to metal streaking after acquiring the images. One company offering a tool which helps reduce movement related artifact after acquisition of the data. The rotation of the cone-shaped X-ray beam and the detector around the patient's head generates large amount of data that is rapidly transferred from the rotating scanning system to the external computers for further processing for visualization in axial, sagittal, and coronal planes, and 3-D reconstruction is done. Images are produced with isotropic submillimeter spatial resolution, and the application-specific software tools are available for use by the dentists.

With advancements, the modern CBCT systems have integrated very well in the dental practice. Smaller footprint of the machine, simplicity of operator training procedures, ease of use, short exposure time, easy patient positioning for scanning, integration into the workflow of the practice, accuracy of information, and availability of relatively simple viewing software have led to the popularity of CBCT systems. However, the CBCT cost and radiation dose are considered to be higher as compared to the conventional 2-D dental imaging procedures. As with any other radiographic technique, the aim is to achieve optimal image quality with the lowest possible radiation dose, which could be challenging. CBCT units are smaller in size and can fit in a dental office with some modification. In majority of the CBCT machines, the patient sits in the chair for the short exposure time.

CBCT digital imaging produces 3-D data of the area of interest with diagnostically acceptable spatial resolution, much lower radiation dose, and cost as compared to the MDCT. For dental practice the first CBCT machine, NewTom 9000 (Quantitative Radiology, Verona, Italy), was developed and introduced in the European market in the late 1990s.

This technology was brought to the market in the United States in 2001. For scanning in the NewTom 9000, the patient had to be in supine position and the X-ray tube and the detector rotated 360° around the patient's head to obtain a relatively larger field of view (FOV) 15 cm × 15 cm volume. The system utilized an image intensifier and a charge-coupled device. The sensor was 8-bit displaying 256 shades of gray. Later developments were made to fabricate CBCT machines with smaller, adjustable FOVs. Later Ortho-CT based on Scanora stand (Soredex Corporation, Helsinki, Finland) made it possible where patient would sit in a chair during the scan. In 2002, 3D Accuitomo unit (J. Morita Corporation, Japan) became available in the European market. In this scanner the patient sat in a chair for exposure, and the FOV size was reduced to 3 cm × 4 cm cylinder [5].

Since then, tremendous improvements have been made in image quality. Currently the CBCT systems offer different sizes of FOVs and 12-bit sensors or more, displaying 4096 shades of gray with 12-bit. CBCT machines use single flat-panel detectors with amorphous silicon. Various FOVs, image acquisition parameters, image reconstruction algorithms, and viewing software programs have become available, providing choices for the user. It has been reported that, at this time in the market, there are around 50 CBCT devices available from 20 manufacturers, which are operating in 20 different countries around the world (Table 1.1) [5]. Today's CBCT units are equipped with head restraining/positioning devices that help better position the patient during the scan to reduce movement artifacts. Software programs have post-processing tools that can be used to minimize image noise artifacts after data acquisition. It is important that the whole dental team be knowledgeable about the availability of these tools in the software. This will potentially reduce the number of re-exposures.

1.3 Acquisition of CBCT Volume

CBCT devices consist of X-ray source (cone-shaped divergent beam) and a 2-D image detector. The X-ray source and the image detector are connected by an arm that rotates around the patient's head during the scan. Rotation varies from 180° to 360°. Typically, the volumetric data is captured with single rotation around the patient's head as the transmitted beam of radiation is aimed at the image detector. Beam collimators either match the size of the detector and the beam size or can be used to further reduce or collimate the field of view.

With most CBCT units, a series of 2-D raw base images or projections are captured. The number of raw images varies from 180 to 600 or up to 1000 in some machines. Exposure times vary from 6 s to 40 s. Many machines have pulsating radiation, which helps reduce the patient dose. The ranges for tube current (mA) and peak voltage (kVp) are 1–15 mA and 85–120 mA, respectively. After processing axial, coronal, and sagittal planes, images appear on the computer monitor as an Explore screen (Fig. 1.2).

Table 1.1 Selected CBCT systems available with larger fields of view (FOVs)

Model	Manufacturer	Voxel mm^3	Detector size/field of view cm
3-D Accuitomo 170	J. Morita	0.125–0.2	4 × 4–17 × 12
Galileos Comfort Plus	Sirona Dental systems	0.25/0.125	15 × 15
I-CAT FLX	Imaging sciences	0.125–0.4	8 × 8–17 × 23
CS 9300	Carestream	90 to 500 μm	5 × 5–17 × 13.5
NewTom 3D	Quantitative radiology	0.08	6 × 6–10 × 10
i3D-Premium	Vatech	0.2, 0.3, 0.4	8 × 8 × 21 × 19
PaX-i3D Pano + CBCT + Ceph	Vatech	0.12–0.3	8 × 8–12 × 9
Picasso Pro	Vatech	0.2–0.3	5 × 5–12 × 9
ProMax3D Max	Planmeca	0.1, 0.2, 0.4	5.5 × 5–17 × 22
KaVo OP 3D Vision	KaVo Dental	0.125–0.4	5 × 8–17 × 23
SCANORA 3D	Soredex	0.13–0.35	5 × 5–24 × 16.5

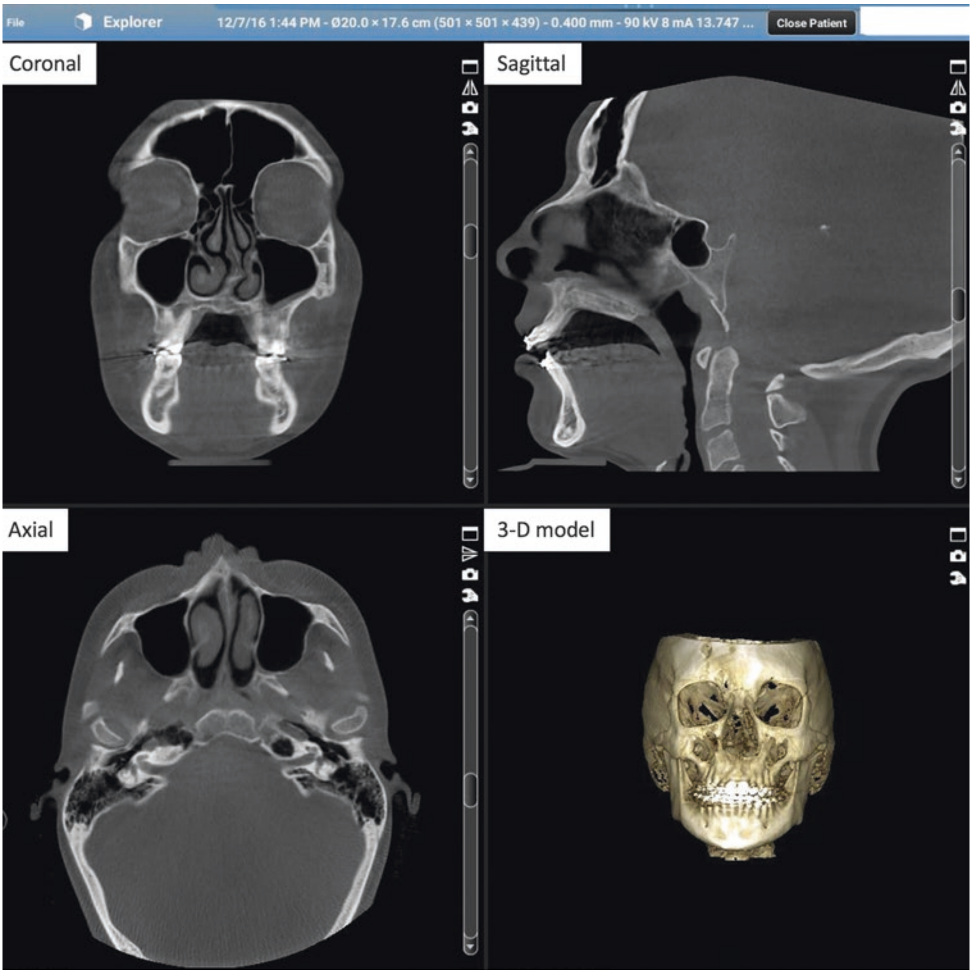

Fig. 1.2 Explore screen from a CBCT machine with large field of view is shown. This is a typical image display in coronal, sagittal, and axial planes

1.4 Image Detectors Used in CBCT Units

The image detector or receptor converts the incoming remnant X-ray photons from the patient into electrical signals. Later computer processing converts these signals into visible images. CBCT machines are equipped with either image intensifier tubes/charge-coupled device (II-CCD) or a flat-panel detector (FPD). II-CCD units are usually bulkier as compared to the FPD. FPD is made up of scintillation crystal screen on a matrix of photodiodes embedded in a solid-state amorphous silicon layer with thin-film transistors. The signal intensity is proportional to the stored charges. The advantages of FPD include higher radiosensitivity, lesser radiation exposure, and better image quality.

1.5 Field of View (FOV)

FOV is the anatomical volume that can be captured by the detector. FOV varies in size. The machines come with various detector sizes. Machines with larger detectors offer larger FOV, with ability to collimate the X-ray beam to a small area or FOV. With collimation of the X-ray beam, the FOV can be reduced to suit the needs, and this reduces the amount of exposure to the patient. Multiple FOV options, ranging from few centimeters to full head size, are available for various clinical scenarios.

Larger detectors tend to be more expensive. Due to the cost factor, some CBCT systems offer smaller detectors with limited FOV. When there is need to acquire the larger FOV, two or more adjacent scans can be made, and the volumes can be stitched together by the computer software to produce a larger FOV.

Decreasing the size of FOV or beam collimation improves image quality by decreasing scatter artifacts in the image. The extent of anatomic coverage should be based on clinical evaluation by the treating clinician. Over collimation or too narrow collimation to achieve smaller FOV may result in excluding essential anatomic structures needed for evaluation, and thus a "not needed" retake of CBCT may be needed. Scarfe and Farman [6] published a FOV categorization of the different CBCT systems according to the CBCT volume height and provided examples of coverage as follows:

- Craniofacial region: Height > 15 cm (extending from the head vertex to the inferior mandibular border).
- Maxillofacial region: 10–15 cm in height (nasion to inferior mandibular border).
- Interarch region: 7–10 cm (extending from the inferior nasal concha to the mandible).
- Single arch/jaw: 5–7 cm (maxillary or mandibular arch only).
- Localized to region of interest: 5 cm or less in height (1–2 teeth and surrounding bone, temporomandibular joints).

FOV can also be classified large for craniofacial coverage (>10 cm in height) and small to medium for dentoalveolar coverage (variable depending on the region of interest <10 cm in height). Smaller volume or FOV should be considered if it addresses the diagnostic needs [7].

1.6 Reconstruction Process and Display of CBCT Images

With a single rotational movement of the CBCT machine used for exposure of 20 s or less, approximately 100 to more than 600 individual frames may be captured by the acquisition computer. A volumetric data set is created with the individual basic frames by a series of algorithms or reconstruction process at the processing computer or the workstation. Both computers are connected via an Ethernet connection for transfer of the acquired individual frames from acquisition computer to the workstation for processing.

For image display, the CBCT units also use HU units. However, in CBCT, the measured density numbers correspond to the grayscale values and do not directly represent HU units. Smaller field of view scans have more discrepancies