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Dental and Maxillofacial Cone Beam Computed Tomography

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42.1 Introduction

Diagnostic imaging is an important adjunct to the clinical assessment of the dental patient. Two-dimensional (2D) planar images from intraoral (periapical and bitewing) and extra-oral (dental panoramic and cephalometric) radiographic techniques are the most commonly acquired (see Section II, Chapter 22). Usually in combination, these images are used to provide a comprehensive radiographic view of the teeth, and their supporting structures, and the jaws. In particular, dental panoramic radiography (DPR) provides a single comprehensive image of both jaws and adjacent maxillofacial structures. However, DPR images suffer the inherent limitations of all 2D projections such as variable magnification and superimposition of anatomical details. In addition, limited spatial resolution, patient positioning errors, and artifacts associated with rotational tomographic acquisition may produce distorted images that may misrepresent anatomic structures and create ghosting artifacts. Figure 42.1 shows two DPR images—one providing an excellent representation of the jaws (a) and a second with distortion due to incorrect patient positioning affecting interpretation (b).

In dentistry, several imaging technologies have been tried for volumetric imaging capability, including stereoscopy, conventional tomography, tomosynthesis, and tuned aperture computed
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9.2 Development of Maxillofacial CBCT Systems

The principles of tomosynthesis providing the theoretical basis of the integration of multiple planar images were described as early as 1934 by Ziedes des Plantes (Ziedses des Plantes 1973, Webber and Horton 1997) (The Italian radiologist A. Vallebona introduced stratigraphy in 1932. See: A. Vallebona. Una modalità di tecnica per la dissociazione radiografica delle ombre applicata allo studio del cranio. Radiol. Med., vol. 17, pages 1090–1097, 1932). The need for faster acquisition of volumetric data for specific tasks, like angiography, using a comparatively less expensive radiation sensor than conventional CT led to the development of the Dynamic Spatial Reconstructor (DSR), conceived as early as 1975 by the Biodynamics Research Unit and finally installed in the Medical Sciences Building on the Mayo Clinic Rochester campus in 1978 (Robb et al. 1980, Robb 1982). However, it was not until the late nineties that four technological developments converged to facilitate construction of affordable CBCT units small enough to be used in the dental office for maxillofacial imaging (Scarfe and Farman 2007):

1. Introduction of X-ray sensors capable of rapid acquisition of multiple basis images: The demands on any X-ray sensor in maxillofacial CBCT for dentistry are hard to fulfill. The sensor must be able to record X-ray photons, read off and send the signal to the computer, and be ready for the next acquisition many hundreds of times within a single rotation. As rotation is usually performed within times equivalent to, or less than, DPR (five to 20 seconds), this necessitates frame rate image acquisition times of milliseconds. Manufacturers that make area X-ray image sensors suitable for maxillofacial CBCT include Hamamatsu Photonics K.K (Hamamatsu City, Japan), Varian Medical Systems (Salt Lake City, Utah, USA), and Samsung (Seoul, South Korea).

2. The development of suitably resilient X-ray generators: The X-ray generators used in maxillofacial CBCT machines are far simpler than those in multi-detector computed tomography (MDCT), with an operating voltage between 80 and 120 kVp. The majority of the units operate toward the lower end of this range, which does not differ substantially from operating parameters in DPR machines. Although the focal spot size is no different than MDCT (nominally 0.3–0.8 mm), the anode is stationary in most maxillofacial CBCT systems, with few exceptions. The tube current is generally much lower than MDCT, which reduces the power of the generator as well as the production of heat. Finally, in most maxillofacial CBCT systems, X-ray generation is pulsed to coincide with the sensor activation. This is preferable as it markedly reduces exposure time and, therefore, heat production (shorter duty cycle) with less radiation dosage to the patient. However, the relatively low power used in this type of X-ray generator provides limitations in image quality. Manufacturers that make X-ray tube heads with high heat capacity suitable for maxillofacial CBCT include Toshiba (Toshiba Electron Tubes and Devices Co., Ltd., Tochigi, Japan), Varian Medical Systems (Salt Lake City, Utah, USA), Samsung (Seoul, South Korea), and J. Morita Corp. (Kyoto, Japan).

3. The evolution of suitable image acquisition and integration algorithms (Feldkamp et al. 1984, Grangeat 1991, Wischmann et al. 2002): The ability to volumetrically reconstruct data from cone beam projections

FIGURE 42.1 Two dental panoramic radiography (DPR) images of different patients showing accurate (a) and distorted (b) representation of the maxillofacial skeleton and jaws due to multiple patient positioning errors, including positioning the patient’s head too far forward and the chin down.

In dentistry, there has been an unprecedented interest in CBCT from all disciplines and specialties. Maxillofacial CBCT has enabled a transition from 2D to volumetric capture, providing three-dimensional (3D) radiographic imaging for the assessment of the craniofacial skeleton and to facilitate dental diagnosis. In addition, largely via the proliferation of third party applications software capable of importing data in Digital Imaging and Communications in Medicine (DICOM) file format, the role of maxillofacial CBCT has now expanded to image guidance of operative and surgical procedures (Scarfe and Farman 2008, Angelopoulos et al. 2012).
acquired along a circular trajectory is a fairly recent accomplishment, associated with the development and introduction of the FDK (Feldkamp–Davis–Kress) algorithm (Feldkamp et al. 1984) (see Section III, Chapter 33 of this book). In MDCT, individual axial slices of the object are sequentially reconstructed using a well-known mathematical technique (filtered back-projection) and subsequently assembled to construct the volume. However, with 2D X-ray area sensors and cone beam geometry, a volumetric dataset is reconstructed from 2D projection data. This is referred to as cone beam reconstruction. The FDK algorithm, which employs a convolution-back-projection method, continues to be the most popular approximate reconstruction scheme for cone beam projections used by most research groups and commercial vendors for maxillofacial CBCT systems in dentistry.

4. The availability of powerful personal computers: Enormous computing power is necessary to apply the FDK algorithm to the vast amount of image data acquired in maxillofacial CBCT acquisition (Aziz et al. 2008). It is only with the introduction of the micro-chip based computer by Gordon Moore and the Windows operating system by Bill Gates that, in the late nineties, small, low-cost computers capable of computational complexity enabled clinical CBCT systems to be manufactured for use in the dental office.

42.2.1 Commercial Introduction of Maxillofacial CBCT Units

While numerous developers were working on adaptation of existing robotic platforms, application of software reconstruction algorithms, and investigating the use of various image sensors for maxillofacial CBCT in the early nineties, these efforts have been largely kept as trade secrets or were under confidentiality agreements at that time. Figure 42.2 summarizes the timeline for the commercial introduction of the initial 25 maxillofacial CBCT units approved by the Food and Drug Administration (FDA) for dentistry in the United States to the end of 2009. While FDA approval is only necessary for the sale of devices in the United States, this graph reflects the rapid influx of different vendors and models into the market.
manufacturers available in the marketplace in the rest of the world, including Europe.

### 42.2.1.1 Early Innovators

A patent application for the first commercially successful maxillofacial CBCT was made by Attilio Tacconi and Piero Mozzo in Italy in 1995, and the system was designed and produced by QR, Inc. of Verona, now a Ceia company (Molteni, R. 2008. pers. comm.). The system was first introduced at SIRM Milano in June 1996 (Farman et al. 2007a,b, Scarfe and Farman 2007), described in the literature in 1998 (Mozzo et al. 1998), and branded as the NewTom DVT 9000, became the first FDA approved, commercially available maxillofacial CBCT device in the United States in 2001. The appearance of the NewTom DVT 9000, shown in Figure 42.3a, is similar to existing MDCT units of the time. This first generation was followed by the NewTom 3G in 2004 and the NewTom VG in 2007. The NewTom DVT 9000/3G versions acquired the scan similarly to MDCT, with the patient supine; however, the VG series acquires images with the patient positioned standing vertically.

In the late nineties, prototypes were also being developed in Japan including the Ortho-CT (Arai et al. 1999), based on a multifunctional maxillofacial tomography unit (Scanora, Soredex, Helsinki, Finland), and Dental 3D-CT (Nakagawa et al. 2002), based on the PSR 9000 (Asahi Roentgen, Kyoto, Japan). In 2000, the Ortho-CT technology was transferred to J. Morita Co. Ltd. through the Nihon University Business Incubation Center (Hashimoto et al. 2003). The original version was called the 3DX multi-image micro-CT (3DX), introduced in the United States in early 2003 as the 3DX Accuitomo XYZ Slice View Tomograph (J. Morita Corp., Kyoto, Japan) and shown in Figure 42.3b. This was the first small field of view (FOV) (3 cm [height] × 4 cm [diameter]), high-resolution maxillofacial CBCT device introduced into the market that acquired volumes with the patient seated. The FOV was increased to more than four times that size with subsequent models. Both the Newtom 9000 DVT and 3D Accuitomo XYZ Slice View Tomograph scanners used image intensifier sensors.

![FIGURE 42.3](image)

The first maxillofacial CBCT device manufactured in the United States, the i-CAT, was initiated at the Engineering School at the University of Michigan (Ann Arbor, Michigan, USA). It was developed as part of the doctoral program by Predrag Sukovic, who received a Small Business Innovation grant from the National Institutes of Health to develop a maxillofacial CBCT system, termed the DentoCAT (Sukovic 2002, Sukovic 2003). Oral and maxillofacial radiologists, Dr. Sharon L. Brooks and Dr. Allan G. Farman acted as dental consultants. Many of the component parts used to construct the prototype were donated by Eric Stetzel, who at the time was owner of a DPR manufacturer (Panoramic Corporation, Fort Wayne, Indiana, USA). When it came to commercialization, ISI (Imaging Sciences International Hatfield, Pennsylvania) stepped in, helped design an ergonomically efficient unit, and within a remarkably short time of approximately six months, commenced commercial production. ISI have subsequently taken a major position in the market for maxillofacial CBCT units worldwide.

Hitachi engineer, Rika Baba, had a major role in helping develop the Hitachi MercuRay (Hitachi Medical Technology, Chiba, Japan) (Seo et al. 2002, Yamamoto et al. 2003) and subsequently in extending the range of Hitachi CBCT products for anatomical sites other than the maxillofacial region. The MercuRay is a relatively large and heavy unit that in Japan has been replaced by the smaller Hitachi CB Throne and was withdrawn from the American market (Yajima et al. 2006, Farman et al. 2008).

### 42.2.1.2 Subsequent Improvements

Early maxillofacial CBCT devices were unimodal, capable of CBCT image acquisition only, and performed scanning with the patient either supine or seated. They were also expensive for dentists to purchase ($150,000 USD or more) compared to DPR devices ($10,000–50,000 USD). While few models were introduced after the introduction of the NewTom DVT 9000 and again between the years 2003 and 2006, as shown in Figure 42.2, since 2007 the number of maxillofacial CBCT units available has exploded onto the marketplace. The most significant innovations have been the introduction of hybrid, multimodal systems based on existing dental panoramic machine structural platforms, such as the CS 9000 3D (Carestream, Atlanta, Georgia, USA) as shown in Figure 42.4, the ability to customize the FOV, micrometer (less than 0.1 mm) resolution enabling high detail of the tooth and supporting structures, and the ability to retrofit digital DPR devices. The use of existing panoramic platforms and smaller sensors with innovations such as off-set geometric scanning and volumetric data stitching has reduced the price of many hybrid units to less than $100,000 USD. Subsequently, at this price point, clinical adoption has soared with over 10,000 units now operating in dental offices in the United States alone. Globally, the number of CBCT units sold is forecast to grow at a compound annual growth rate of approximately 11%, generating up to $841 million in annual revenue by 2021 (His Markit Technology 2015, Zion Research 2016).

### 42.3 Available Devices

As of late 2016, there were more than 50 maxillofacial CBCT devices commercially available specifically for dentistry,
42.4 Specific Modifications to Maxillofacial CBCT Devices

The general geometric configuration and mechanics, X-ray detection, and digital data reconstruction and display for maxillofacial CBCT are similar to those described in Chapter 3.4. A rotating platform supports the synchronous single rotation of an X-ray source and a reciprocating area sensor around a fixed axis of rotation centered within the patient’s head. A divergent pyramidal- or cone-shaped beam of ionizing radiation is directed through the middle of the region of interest (ROI) onto an area X-ray sensor on the opposite side, with the FOV being determined by the physical collimation applied and sensor size. During the rotation, many single, sequential planar projection images constituting the raw primary data are acquired of the FOV. The individual image projections (basis, frame, or raw images) together are referred to as the projection data. These data are initially processed (primary reconstruction) by software algorithms, including FDK, to create a 3D volumetric dataset composed of cuboidal volume elements (voxels). Orthogonal sectioning of the volumetric dataset to provide characteristic images in axial, coronal, and sagittal planes is referred to as secondary reconstruction. Numerous specific modifications to this acquisition scheme have been incorporated into maxillofacial CBCT for dentistry.

42.4.1 X-ray Tube and Exposure

Technically, the simplest method of acquiring images in a single scan is to use a constant beam of radiation during the rotation and to allow the X-ray sensor to sample the attenuated beam during its trajectory. Alternately, the X-ray beam may be pulsed to coincide with the sensor activation or sampling. This is preferable in dentistry to reduce patient dose and the impact of sensor afterglow, and means that the actual exposure time is less than the total scanning time. This technique can reduce patient radiation dose considerably. Pulsed X-ray beam exposure is a major reason for considerable variation in reported maxillofacial CBCT dosimetry results. Pulsed systems have substantially reduced tube loading and, therefore, less time is necessary between patients. In addition, a greater number of frames can be acquired with a faster rotation speed, potentially reducing patient motion artifacts.

42.4.2 Image Sensor

Current maxillofacial CBCT units use an indirect capture system as the image sensor. An indirect system consists of a scintillator medium that converts X-ray radiation into visible light and a photon sensor. Early maxillofacial CBCT systems used imaging intensifiers (II) as the photon sensor. These systems tend to be relatively large and bulky and most frequently result in circular basis image areas (spherical volumes) rather than rectangular ones (cylindrical volumes). Few units now incorporate II sensors. Currently, most CBCT units use a combination of a thin layer of scintillation material and flat-panel sensors (FPS) using either amorphous silicon or complementary metal oxide semiconductor (CMOS) array technology. Low dose area X-ray sensors are specifically manufactured for CBCT dental applications by several companies, including Teledyne DALSA (Santa Clara, California, USA) and e2V (Chelmsford, United Kingdom). The configuration of such sensors is less complicated and offers greater dynamic range and reduced peripheral distortion than II based systems.

A principal determinant of resolution, and therefore detail, of maxillofacial CBCT imaging is the individual volume element or voxel acquired, which results in the formation of the volumetric dataset. In maxillofacial CBCT imaging, volumetric voxel dimensions are dependent on both the acquired resolution and reconstructed resolution. The acquired resolution is isotropic for maxillofacial CBCT systems and always submillimeter, ranging from a voxel size range of 0.4–0.25 mm (standard resolution) to less than 0.1 mm (high-resolution). The acquired voxel dimensions are a reflection of the pixel size of the image sensor. Maxillofacial CBCT systems with smaller pixels capture less X-ray photons and result in more image noise. Consequently, maxillofacial CBCT imaging using higher resolutions may use higher dosages to achieve a reasonable signal-to-noise ratio for diagnostic image contrast and spatial resolution quality. In general, more basis images are needed during high-resolution scans, which increases acquisition time.
42.4.3 Geometric Configurations

In the most basic CBCT configuration, the central ray of the X-ray beam from the generator is directed through the middle of the ROI, and the transmitted, attenuated radiation is projected perpendicular to the middle of the area image receptor on the opposite side. Data are acquired from a rotational scan of an X-ray source and a reciprocating area sensor synchronously around a fixed axis of rotation centered within the patient’s head. The trajectory arc varies from 180° to 720°. However, to enable scanning of a ROI greater than the FOV of the sensor, various geometric configuration modifications are incorporated into a number of maxillofacial CBCT devices to reduce unit production cost by using a smaller sensor system.

- **Stitching**: One method involves obtaining data from two or more separate scans, superimposing overlapping CBCT data volumes using corresponding fiducial reference landmarks (referred to as either “bio-image registration” or “mosaicing”) and fusing adjacent image volumes to create a larger volumetric dataset, either in the horizontal or in the vertical dimension. Automatic stitching can be vertical (e.g., Romexis Stitching Program, Planmeca Oy, Helsinki, Finland), as with the acquisition software for the first generation i-CAT (iCAT Classic, Imaging Science International, Hatfield, Pennsylvania, USA) when a vertical extended FOV was employed, or horizontal, as for the mandibular arch scan acquired by the limited FOV CS 9000 3D (Carestream Dental, Atlanta, Georgia, USA). The disadvantage of stitching overlapped regions is that such overlapped regions are imaged twice (i.e., over scanned), resulting in double the radiation dose to such regions.

- **Off-axis geometry**: A second method involves positioning of the isocenter (i.e., the rotational center of the FOV) eccentrically to provide an off-axis geometry. In this configuration, a smaller area sensor is used and offset to an asymmetrically collimated beam. In this arrangement, only a portion of the patient’s vertical or horizontal ROI is scanned, such as for the second generation i-CAT (iCAT Next Generation Imaging Science International, Hatfield, Pennsylvania, USA), or the full craniomaxillofacial scan mode, or the Scanora 3D (SOREDEX, Tuusula, Finland). Off-set imaging can be

### TABLE 42.1

<table>
<thead>
<tr>
<th>Unit</th>
<th>Model(s)</th>
<th>Manufacturer/Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuitomo</td>
<td>3D Accuitomo—XYZ Slice View Tomograph, MP, FPD</td>
<td>J. Morita Corp., Kyoto, Japan</td>
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<tr>
<td></td>
<td>3D Accuitomo 170, Veraviewpocs 3D R100, Veraviewpoc 3D F40</td>
<td></td>
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<tr>
<td>Acteon</td>
<td>X-Mind Trium</td>
<td>Acteon North America, Mt Laurel, New Jersey, USA</td>
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<td>Asahi Roentgen</td>
<td>Auge Solio, Alioth, Alphard 3030 (PSR 9000N), Alphard 2520</td>
<td>Asahi Roentgen Ind. Co. Ltd., Kyoto, Japan</td>
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<td>Belmont</td>
<td>Bel-Cat, Bel-Cat PA, Bel-Cat CM</td>
<td>Takara Belmont Corporation, Somerset, New Jersey, USA</td>
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<tr>
<td>Carestream</td>
<td>CS 81003D, CS 9000, CS 9300, CS9500</td>
<td>Carestream Dental, Atlanta, Georgia, USA</td>
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<tr>
<td>CRANEX</td>
<td>3Dx, 3D, and 3D for Endo, Scanora 3D</td>
<td>SOREDEX, Tuusula Finland</td>
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<tr>
<td>Galileos</td>
<td>Comfort, Compact, ComfortPLUS, Orthophos XG 3D</td>
<td>Sirona Dental Inc., Charlotte, North Carolina, USA</td>
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<tr>
<td>Gendex</td>
<td>GXCB-500, GXCB-500 HD, GXPD-800, GXPD-700 with 3D CBCT</td>
<td>Gendex Dental Systems, Hatfield, Pennsylvania, USA</td>
</tr>
<tr>
<td>Hitachi</td>
<td>CB MercuRay/CB Throne</td>
<td>Hitachi Medical Systems, Tokyo, Japan</td>
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<tr>
<td>i-CAT</td>
<td>Classic, Next Generation (Model 17–19, Platinum), i-CAT FLX, i-CAT FLX MV</td>
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<td>I-MAX</td>
<td>I-MAX Touch 3D</td>
<td>Owandy Corporation, Paris, France</td>
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<td>3D eXam, 3D eXam+</td>
<td>KaVo Dental Corp., Biberach, Germany</td>
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<td>Newton</td>
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<td>QR, Inc., Verona, Italy (a Cefla company)</td>
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<td>OP 300</td>
<td>OP 300, OP 300 Maxio 3D</td>
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<td>Biolase</td>
<td>DaVinci Imaging 3D</td>
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<td>Panoramic Corp.</td>
<td>Encompass Eagle 3D</td>
<td>Panoramic Corporation, Fort Wayne, Indiana, USA</td>
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<td>PreXion (Fine Cube)</td>
<td>PreXion3D Elite, PreXion 3D Eclipse</td>
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<td>Promax</td>
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<td>Planmeca OY, Helsinki, Finland</td>
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<td>MyRay</td>
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<td>Vatech, Giheung-gu, Korea</td>
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</tbody>
</table>

* No longer manufactured/unavailable.
configured separately, vertically or horizontally, in both dimensions (NewTom VGi, QR srl, Verona, Italy), with or without a non-perpendicular sensor arrangement.

- **Partial arc rotation angle:** Most reconstruction algorithms (e.g., FDK algorithm) require that projection data be acquired from a complete circular trajectory or a scan arc of 360°. However, it is possible to reduce the rotation angle of the CBCT gantry to as low as 180°, which will provide sufficient information to reconstruct a volumetric dataset. This approach potentially reduces the scan time and allows the incorporation of maxillofacial CBCT into a panoramic robotic platform to produce a hybrid, multimodal system. Most maxillofacial CBCT systems are now multimodal, based on the panoramic platform, and presently use a rotation of less than 360°. Images produced by this method may have greater noise and suffer from reconstruction interpolation artifacts. Maxillofacial CBCT units are available either providing options for both partial or full rotation angles, or providing a fixed full or partial rotation angle only.

### 42.5 Maxillofacial CBCT Device Configurations

There are numerous maxillofacial CBCT manufacturers offering different unit configurations, as shown previously in Table 42.1. Maxillofacial CBCT systems can be categorized according to the orientation of the patient during image acquisition and whether they operate on dedicated or hybrid panoramic platforms. In addition, units can be categorized according to the maximum volume of acquisition or FOV available.

Most CBCT units are constructed such that acquisition is performed with the patient standing or sitting. Few devices are available where the patient is scanned in the supine position. Supine units occupy a larger surface area or physical footprint and may not be accessible for patients with physical disabilities. Standing units may not be able to be adjusted to a height to accommodate wheelchair bound patients. Seated units are the most comfortable, however fixed seats may not allow scanning of physically disabled or wheelchair bound patients. Perhaps more important than patient orientation is the head restraint mechanism used, as patient motion may limit optimal resolution.

Maxillofacial CBCT systems can also be divided into stand-alone or hybrid multimodal systems that combine digital panoramic and/or cephalometric radiography with small-to-medium FOV CBCT imaging. These units provide substantial cost savings as existing robotic panoramic platforms can be re-engineered and smaller, less expensive sensors used.

Finally, maxillofacial CBCT units can also be assigned into four broad categories based on volume of acquisition, determined by a combination of vertical and horizontal dimensions of the FOV:

- **Extended (craniofacial):** Covers most of the craniofacial skeleton, at least from below the hard tissue of the chin to the nasion. Usually greater than 15 cm in height.
- **Large (maxillofacial):** Extends to include both jaws and dental arches and portions of the maxillary sinuses. Height ranges from greater than 10 cm to equal to or less than 15 cm.
- **Medium (dento-alveolar):** Single or inter-arch region ranging from 5 to 10 cm vertically, incorporating the maxilla and/or mandible. Usually greater than 50 cm³ and less than 150 cm³ beam area at the isocenter.
- **Small (localized, focal, or limited):** Approximately 5 cm or less vertical height covering localized regions such as three to four teeth and surrounding alveolus or the temporomandibular joints. Usually less than 50 cm³ beam area at the isocenter. Because of the amount of data generated (which demands exponentially greater computational power) and greater exposure required, high-resolution imaging (nominal voxel resolution less than 0.125 mm) is usually achievable only when FOV is reduced to small FOVs.

### 42.6 Technique Considerations

Operation of maxillofacial CBCT devices is technically simple and similar, in many respects, to DPR. However, operator requirements differ markedly between countries. For example,

| TABLE 42.2 |
|---|---|---|
| Technique Phase | Similarities | Differences |
| Technique factors | Determined before exposure and based on patient age and build; kVp and mA settings determine image quality and patient radiation dose. | Maxillofacial CBCT offers more choices than panoramic including FOV, arc trajectory, resolution, and number of projection images. Scan factors for CBCT are adjusted to be task specific. |
| Patient preparation | Patient standing or seated, head stabilized, position critical to resultant image. Bite block always used to stabilize head position. | Patient may also be supine. Instead of bite block, head position may be stabilized by chin rest. |
| Radiation protection | Lead torso apron used. | Thyroid collar is desirable, especially for maxillary scans if possible. Scan time may be greater than DPR and motion artifact may be more likely to occur. |
| Exposure | Patient informed to keep still. | Image calibration may be required. Secondary reconstruction is required before viewing (30 s–2 min). Secondary orthogonal images must be reformatted. Data is interactive (contrast, brightness, image mode). Resultant data can be re-oriented to compensate for head position. |
| Image visualization | Image viewed immediately. | |

**Abbreviations:** DPR: dental panoramic radiography; FOV: field of view; CBCT: cone beam computed tomography.
in many jurisdictions in the United States, maxillofacial CBCT devices can be operated by dental auxiliaries with nominal radiographic qualifications, whereas in some European countries they can only be operated by dentists with special training in CBCT. Unlike DPR, maxillofacial CBCT units exhibit wide differences in available technical parameters. Table 42.2 shows the similarities and differences between the operation of DPR machines as compared to maxillofacial CBCT devices.

The choice of specific technical parameters to optimize image quality and minimize exposure for a specific imaging task is referred to as an acquisition protocol. Practitioners and operators using maxillofacial CBCT must have a thorough understanding of the operational parameters and the effects of these parameters on image quality and radiation safety (Carter et al. 2008).

### 42.6.1 Exposure

Four exposure parameters determine the quality and quantity of the X-ray beam. Two of the factors, focal spot size and beam frequency, are equipment dependent whereas the other two, milliamperage (mA) and kilovoltage (kV), are usually operator controlled. However, the relatively low power of X-ray generators used in maxillofacial CBCT and pulsed production provides limitations in image quality. CBCT manufacturers either provide a selection of “fixed” exposure settings (e.g., PreXion, PreXion Co., Ltd., Tokyo, Japan; GALILEOS, Sirona AG, Bensheim, Germany; NewTom 5 g/VGi, QR, Inc. [a Cefla company], Milano, Italy) or allow “manual” adjustment of kV and/or mA. Most CBCT units operate in the range less than 90 kV, whereas a few can operate at higher kV up to 120 kV. The range of mA settings is extensive, with most operating at less than 12 mA; however, some operate as high as 20 mA. In general, low kV units operate at higher mA. Higher kV units theoretically produce images with a higher contrast to noise ratio, particularly at lower exposures, because of increased photon count and a decreased absorption ratio (Pauwels et al. 2014). Exposure parameters should be appropriate for both the given patient size and to the specific diagnostic task. While mA may be increased on some units and is suggested to compensate for increases in patient size, the effective dose increases proportionately, almost in a 1:1 ratio. Adjustment of kV has an even greater effect on dose than mA does, with each increase in 5 kV approximately doubling dose if all other parameters remain the same.

Automatic exposure control (AEC) is a dose reduction strategy used in most MDCT devices to optimize patient doses. AEC attempts to adjust and customize (i.e., modulate) tube current (mA) specifically for each patient according to the radiation intensity detected, either by using a short pre-examination exposure or dynamically during the rotation. Few CBCT devices implement AEC (e.g., NewTom-FP; Quantitative Radiology, Verona, Italy) and, of those, mAs is adjusted based on a single 2D scout image (Pauwels et al. 2015a,b).

### 42.6.2 Number of Basis Images

The number of images comprising the projection data throughout the scan is determined by the frame rate (number of images acquired per second), the completeness of the trajectory arc, and the speed of the rotation. The number of projection scans comprising a single scan may be fixed or variable. More projection data provide more information to reconstruct the image, allow for greater spatial and contrast resolution, increase the signal-to-noise ratio producing “smoother” images, and reduce metallic artifacts. However, this is usually accomplished with a longer scan time, a proportionately higher patient dose, a longer duty cycle between patients to allow for cooling of the generator tube, and a longer primary reconstruction time.

### 42.6.3 Scan/Exposure/Reconstruction Time

Because CBCT units acquire all projection images in a single rotation, the actual period in which the gantry revolves around the patient’s head, or scan time, ranges from approximately five up to 40 seconds. Ideally, scan time should be comparable to DPR so that artifacts associated with subject movement are minimized. Exposure time is usually less than scan time, being the actual time that the X-ray generator is on, producing X-radiation. This ranges from two to approximately 12 seconds, with a maximum of up to 34 seconds. Reconstruction time is the time taken by the workstation computer for dataset reconstruction and varies depending on the FOV, the number of basis images acquired, resolution, and reconstruction algorithm and ranges from less than 30 seconds to over five minutes. The application of secondary reconstruction methods, such as iterative reconstruction for streak artifact reduction, can run considerably more than five minutes (Dong et al. 2013).

#### 42.6.4 Frame Rate

Higher frame rates provide images with less artifacts and better image quality. High frame rates demand sensor arrays with pixels sensitive enough to capture adequate radiation to register a high signal-to-noise output and transmit the voltage to the analog-to-digital converter—all within a short arc of exposure. For a given maxillofacial CBCT unit, a greater number of projections increase the amount of radiation a patient receives proportionately. Within the cost limitations of solid-state sensors used in maxillofacial CBCT construction and the need for short scanning time in a clinical setting, the number of images available for construction ranges from 150 to over 1000.

### 42.6.5 Rotation Angle

Most reconstruction algorithms (e.g., the FDK algorithm) require that projection data are acquired from a complete circular trajectory or a scan arc of 360°. However, it is possible to reduce the rotation angle of the maxillofacial CBCT gantry and still reconstruct a volumetric dataset. This approach potentially reduces the scan time and allows the incorporation of maxillofacial CBCT into a panoramic platform to produce a hybrid system. Images produced by this method may have greater noise and suffer from reconstruction interpolation artifacts. CBCT units are available providing fixed or variable rotation angles. Fixed rotation angle units may be complete 360° or partial trajectory arcs. Units providing variable rotation angles usually have two options; a complete or partial rotation partial angle.
42.6.6 Field of View (FOV)

The dimension of the FOV, or scan volume, is primarily dependent on the sensor size and shape, beam projection geometry, gantry motion, and the ability to collimate the beam. The shape of the scan volume is determined by the sensor technology and acquisition method. Spherical FOVs are characteristic of II sensors. Most flat panel detector (FPD) sensor systems produce a cylindrical FOV with a height and circular diameter. A few devices limit the FOV to the jaw shape, restricting the ROI to the dental structures. The CS 9000 3D (Carestream, Atlanta, Georgia, USA) stitches three cylindrical FOVs from consecutive exposures in the horizontal axis, enough to cover a single jaw. An alternate method to cover the shape of the jaws is provided by the Accuitomo R100 (J. Morita Corporation, Kyoto, Japan). This maxillofacial CBCT device is the only unit that produces a convex triangular shape from a complex motion of the gantry during exposure, referred to as 3D Reuleaux Full Arch (patent pending; J. Morita Corporation, Kyoto, Japan).

Collimation of the primary X-ray beam limits X-radiation exposure and is highly desirable, such that an optimal FOV can be selected for each patient based on disease presentation and the ROI. Reduction in the FOV can usually be accomplished mechanically or, in some instances, electronically. Mechanical reduction in the dimensions of the X-ray beam can be achieved by either pre-irradiation (reducing primary radiation dimensions) or post-irradiation (reducing the dimensions of the transmitted radiation, before it is detected) collimation. Currently, most maxillofacial CBCT units use adjustable metallic shields as primary collimation at the radiation source. Electronic collimation involves elimination of data recorded on the sensor peripheral to the area of interest. In this case, there is no physical reduction in irradiation of the ROI by physical means. Both techniques reduce the amount of data for computational purposes and reduce reconstruction time; however, only pre-irradiation physical collimation results in reduced patient radiation.

42.7 Device Limitations

The image quality of maxillofacial CBCT devices is dependent on spatial and contrast resolution, image noise, and artifacts. Several interacting acquisition variables have an effect on image quality.

42.7.1 Acquired/Reconstructed Spatial Resolution

CBCT units provide voxel resolutions that are isotropic—equal in all three orthogonal dimensions. Maxillofacial CBCT imaging produces images with sub-millimeter voxel resolution ranging from 0.4 mm to as low as 0.076 mm. Because of this, subsequent secondary (axial, coronal, and sagittal) and multi-planar reformatted images achieve a level of spatial resolution that is accurate enough for measurement in maxillofacial applications where precision is important, such as the assessment of bony ankylosis of teeth. As a rule of thumb, tasks requiring high spatial resolution should be performed at a voxel resolution of 0.2 mm or lower.

The spatial resolution of maxillofacial CBCT systems is primarily a function of sensor nominal pixel size and fill factor; however, factors such as beam projection geometry, patient X-ray scatter, sensor motion blur, X-ray generator focal spot size, number of basis images, and reconstruction algorithm all contribute to the final maximum achievable resolution. Most manufacturers provide options for varying resolution of CBCT data. However, sensors cannot, per se, be altered to change the number of pixels within the area matrix that capture X-rays. For a given projection geometry and FOV, then the acquired dataset is always acquired at the highest resolution. In some CBCT units, resolution can be increased by altering projection geometry, reducing the object to focal spot distance. Electronic pixel binning is often used to provide reconstructed images with voxel resolution less than that acquired. Pixel binning is the process of combining charge from adjacent pixels from the sensor during readout. The two primary benefits of binning are improved contrast due to an improved signal-to-noise ratio and the ability to increase frame rate, albeit at the expense of reduced spatial resolution. While higher resolution may be considered desirable for many tasks in dentistry, it should be used judiciously for procedures demanding accuracy to the level of detail of approximately the periodontal ligament space (i.e., approximately 0.2 mm or less). Images taken at high-resolution often have reduced brightness and contrast, increased noise (when displayed in thin slice thickness), and require increased reconstruction time. While increased image resolution in some maxillofacial CBCT units does not affect changes in exposure parameters, some manufacturers incorporate reduced-dose exposure protocols for low-resolution settings.

As CBCT data is acquired volumetrically, it is possible to reconstruct and display multi-planar images at resolutions higher than that at which they were originally acquired. However, this introduces additional noise. This is referred to as reconstructed resolution. Currently, only one maxillofacial CBCT device allows for reconstructed resolution—the 3D Accuitomo 170 (J. Morita Corp., Kyoto, Japan) “zoom reconstruction” feature is unique in that, for large FOV acquisitions, often displayed at low resolutions to reduce reconstruction time and file size, a small ROI within the original scan can be identified and a small FOV with an 80 µm voxel resolution can be reconstructed from the original data. Figure 42.5 shows an example of the clinical application of this reconstructed resolution feature.

As with other forms of digital radiography, care should be taken to distinguish between acquired nominal resolution based on specified pixel or voxel values and the actual acquired resolution achieved due to the various constraints within the total imaging chain and reconstructed resolution.

42.7.2 Contrast Resolution

Numerous factors limit the contrast resolution of CBCT. The inherent geometric configuration of CBCT image acquisition produces marked patient scatter radiation. This is a significant factor in reducing the contrast of any maxillofacial CBCT system. In addition, because of the divergence of the X-ray beam over the area sensor, there is non-uniformity in absorption on the area sensor, with greater signal-to-noise ratio (less noise) on the cathode side of the image relative to the anode side (heel effect). Further, numerous inherent FPD based artifacts affect linearity in response to X-radiation. For these reasons, and the limited kV...
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and mA of CBCT, maxillofacial CBCT images lack adequate gray scale sensitivity to discern subtle differences between soft tissues, such as between fluids and solid tumors, though are excellent for demonstrating air to soft tissue boundaries.

Gray scale intensity values measured on CBCT images do not directly represent Hounsfield units (HU), the relative density of body tissues according to a calibrated gray-scale level, based on normalized-HU values for air (−1000 HU), water (0 HU), and dense bone (+1000 HU) (Bryant et al. 2008, Nackaerts et al. 2011, Molteni 2013). While these conditions limit the application of current maxillofacial CBCT imaging to the assessment of osseous structures, several techniques and devices are currently being investigated to suppress these effects or derive HU from gray density levels in dental CBCT (Lagravere et al. 2006, 2008, Mah et al. 2010, Molteni 2013).

42.7.3 Noise

Image noise refers to the non-uniform density differences in a radiographic image and may affect diagnostic efficiency. Noise represents itself in inconsistent attenuation (gray) values in the projection images. Noise can be generated from anywhere along the imaging chain; however, in maxillofacial CBCT, there are three principal sources.

- **Inhomogeneity of incident X-ray photons**: The spectra of incident X-ray photons have substantial fluctuations in both quality and quantity over the area sensor; this is a direct result of increased scatter radiation from divergent X-ray projections and lower overall projection beam energy. This variation in X-ray profile over the sensor area, known as flux, results in an uneven distribution of gray values on the resultant basis image. CBCT imaging uses mA settings approximately one tenth of those used with MDCT, resulting in CBCT lower beam attenuated energies with greater variability, which results in substantially reduced signal-to-noise ratios compared to MDCT.

- **Electronic noise**: Solid-state sensors are imperfect and gradually accumulate charge over a period of inactivity. This can dilute the received signal when acquisition occurs, presenting as noise.

- **Photon count noise**: The total number of photons recorded for a given maxillofacial CBCT system representing a specific voxel may also determine the degree of noise within the system and depends on considerations of voxel size, sensor efficiency, quantum mottle, number of basis images, and completeness of the rotational scan.

42.7.4 Artifacts

An artifact is any distortion or error in an image that is unrelated to the subject being studied. Schulze et al. (2011) provide an excellent overview and discussion of maxillofacial CBCT artifacts. Artifacts can be classified according to where they occur in the imaging chain.

- **X-ray beam related**: Numerous artifacts are produced in association with the interaction of the X-ray beam with high density materials (HDM) such as dental amalgam, crowns, titanium dental implants, and composite resin often present in the jaws.

  - **Scatter**: When X-ray photons are diffracted from their original path after Compton interaction with HDM, they add to the primary intensity of the X-ray beam and produce dark linear streaks in reconstructed images. Scatter is more prominent in larger array sensor systems, such as CBCT, reduces overall soft tissue contrast, and affects the density values of all voxels in the ROI.

  - **Beam hardening**: As polychromatic X-ray photons are attenuated by HDM, the overall beam energy increases as lower energy photons are absorbed in preference to higher energy photons. This results in two types of artifact: (1) distortion of metallic structures due to differential absorption, known as a cupping artifact and, (2) streaks and dark bands radiating from HDM. This artifact is more pronounced on CBCT images because these systems have lower mean kV compared to CT. In clinical practice, it is advisable to reduce the FOV to avoid scanning regions susceptible to beam hardening (e.g., metallic restorations, dental implants). This can be achieved by collimation, modification of patient positioning, separation of the dental arches,
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- Extinction: These artifacts, also known as missing value artifacts, occur in regions where beam hardening artifacts are additive to a level such that there is little photon energy recorded and appear as dark voids. This is prominent in regions where there are adjacent HDMs and there is crossover of the X-ray projection beam (e.g., adjacent titanium implants, dental restorations).

- Exponential edge gradient effect: This effect occurs whenever long sharp edges of high contrast are encountered. This occurs commonly in maxillofacial imaging such as at metallic crown borders. The most common effect is dark streaks emerging from single straight edges in the direction of the projection, however dense streaks from pairs of edges are possible.

- Patient related artifacts: Patient motion during rotation of the maxillofacial CBCT gantry rotation can cause misregistration of data and, most commonly, appears as a “double contour.” Figure 42.6 illustrates the appearance of double contouring and the effect on the image quality of subsequent reconstructions. Patient motion can be minimized by use of a head restraint and by using as short a scan time as possible. The smaller the acquisition resolution of the volumetric dataset and the longer the scan time, the more likely motion artifacts are to appear. Subtler motion artifacts, presenting as unsharpness and loss of resolution, may also originate from disparities in motion of the components of the system, which may occur in the vertical direction due to dissimilarities in weight between the sensor system and X-ray generator. This type of artifact is usually prevented from occurring by the use of dampening systems. Repeated use of maxillofacial CBCT equipment over time may result in slight configuration changes, and components may need to be periodically re-aligned.

- Scanner related artifacts: Typically, scanner related artifacts present as circular or concentric dark rings in the axial plane, centered about the location of the axis of rotation. They result from imperfections in scanner detection or poor calibration.

- Cone beam related artifacts: The beam projection geometry of CBCT and image reconstruction method produce numerous cone beam related artifacts.

- Partial volume averaging: This is a feature of both MDCT and maxillofacial CBCT imaging. It occurs when the selected voxel resolution of the scan is greater than the spatial or contrast resolution of the object to be imaged. In this case, the pixel is not representative of the tissue or boundary, however becomes a weighted average of the different CT values. Boundaries in the resultant image may present with a “step” appearance or homogeneity of pixel intensity levels. Partial volume averaging artifacts occur in regions where surfaces are rapidly changing in the z direction, for example in the temporal bone. Selection of the smallest acquisition voxel can reduce the presence of these effects.

- Under-sampling: This can occur when too few basis projections are provided for the reconstruction. A reduced data sample leads to misregistration and sharp edges and noisier images due to aliasing, where fine line striation patterns (moiré patterns), appear in the image, particularly in the periphery. This effect may not degrade the image severely; however, when resolution of fine detail is important, under-sampling artifacts needs to be avoided as far as possible by maintaining the number of basis projection images.

- Cone beam effect: The cone beam effect is a potential source of artifacts, especially in the peripheral portions of the scan volume. Because of the divergence of the X-ray beam as it rotates around the patient in a horizontal plane, projection data are collected by each sensor pixel. The amount of data corresponds to the total amount of recorded attenuation along a specific beam projection angle as the scanner completes an arc. The total amount of information for peripheral structures is reduced because the outer row sensor pixels record less attenuation, whereas there is more information recorded for objects projected onto the more central sensor pixels. This results in image distortion, streaking artifacts, and greater peripheral noise. This effect can be minimized by the manufacturers’ incorporation of various forms of cone beam reconstruction. Clinically, it can be reduced by positioning the ROI adjacent to the horizontal plane of the X-ray beam and collimation of the beam to an appropriate FOV.

- Local tomography: In small FOV geometric configurations, inconsistencies can occur in the reconstructed volume because structures that lie adjacent and outside the FOV are only irradiated over small angular distances, yet are still incorporated in the back-projection algorithm.
• Off-set projection: To reduce costs, yet provide a relatively large FOV, the X-ray generator/sensor system gantry may be offset to the center of rotation. This results in a central region being reconstructed from projections from a complete rotation, while more peripheral areas are constructed from images acquired from angles of 180–360°, depending on their distance from the center of rotation. This provides images that may show abrupt transition between the two zones as border ring artifacts.

42.8 Patient Radiation Dose Considerations of Maxillofacial CBCT

The radiation dose in maxillofacial CBCT has been extensively reported in the literature using a variety of models, dose quantities, and measurement methodologies. The effective dose, E, (the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body) measured in microSieverts (µSv), is the most widely used metric to express radiation-induced risk. Table 42.3 summarizes the reported range of effective dose for numerous maxillofacial CBCT devices according to FOV. Reported adult effective doses for any protocol ranged from 46 to 1073 µSv for extended FOVs, 9 to 548 µSv for large FOVs, 4 to 421 µSv for medium FOVs, and 5 to 297 µSv for small FOVs (Ludlow et al. 2015). The results from these studies indicate that there is a wide range in patient dose for maxillofacial CBCT. This reflects the range of available maxillofacial CBCT device configurations (beam filtration, receptor technology, resolution) and parameters used in clinical practice, such as FOV, exposure (kVp and mA), and acquisition (e.g., rotational arc, number of basis images) settings.

As a comparison, and in order of decreasing magnitude, doses for DPR range from 14 to 38 µSv, for cephalometric radiography are 5.1 to 5.6 µSv, and for a four image bitewing radiographic series are approximately 5 µSv (Ludlow and Ivanovic 2008, Ludlow et al. 2015).

<table>
<thead>
<tr>
<th>Device</th>
<th>Extended FOV</th>
<th>Large FOV</th>
<th>Medium FOV</th>
<th>Small FOV</th>
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<tbody>
<tr>
<td>3D eXam</td>
<td>72–156</td>
<td>107</td>
<td>45–170</td>
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<tr>
<td>Alphard VEGA</td>
<td>69–288</td>
<td>69–184</td>
<td>20–94</td>
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<td>CB Mercuray</td>
<td>569–1073</td>
<td>60–548</td>
<td>60–145</td>
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<tr>
<td>CS 9000</td>
<td>76–204</td>
<td>75</td>
<td>35–127</td>
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<td>CS 9300</td>
<td>93–260</td>
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<td>76–166</td>
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<tr>
<td>Galileos Comfort Plus</td>
<td>38–154</td>
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<td>27–133</td>
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<td>Galileos Comfort</td>
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<td>Galileos</td>
<td>70–128</td>
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<td>61–134</td>
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<td>67–129</td>
<td>9–171</td>
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<td>Newtom VG</td>
<td>83</td>
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<td>Veraviewepoc 3D</td>
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a. 15 cm height.
b. >10 cm–≤15 cm height.
c. ≤10 cm height, >50 cm² beam area at isocenter.
d. ≤10 cm height, ≤50 cm² beam area at isocenter.

42.8.1 Dose Reduction Strategies for Maxillofacial CBCT

42.8.1.1 Justification


42.8.1.2 Optimization

A wide dose range implies a great potential for optimization, and several dose-saving strategies have been proposed, including (European Commission 2012):

- Reducing mA: Lowering exposure mA in CBCT devices results in a proportional decrease in patient dose. Although noise increases, clinical image quality may often remain acceptable for moderate or even large reductions in mA compared to the manufacturer’s recommended setting (Pauwels et al. 2015a,b). The level of mA reduction achievable with appreciable reduction in image quality is equipment specific (Goulston et al. 2016). Pauwels et al. (2017) propose a possible reduction in mA (using a fixed 90 kVp exposure) ranging from 7 to 50%, based on an exponential relation between head size and mA. Reductions in mAs are more dose-efficient than kVp reductions.

- Increasing kVp: Increasing the tube voltage may result in a decrease in skin and effective dose but an increase in scatter due to a proportionally higher percentage of Compton interactions. This is undesirable as it may reduce image quality associated with image noise. However, higher tube voltage may be clinically desirable, particularly in the assessment of bone associated with dental implants, as it reduces the beam hardening effect (Ludlow 2011).

- Reducing the number of acquisition projection images: For a specific CBCT device, selection of a lower scan time results in less acquisition projection images and a proportional decrease in patient radiation exposure (Ludlow and Walker 2013). However, images reformatted from volumetric datasets reconstructed with reduced projection images generally have lower spatial resolution, reduced contrast, and increased noise.

- Reduced trajectory arc: Some CBCT devices allow partial trajectory arc rotations (180°) instead of a full rotation (360°). This modality offers a 50% dose reduction to the patient.

- Collimation: Patient dose is markedly reduced with collimation of the FOV to the ROI. While the range of doses for various CBCT devices for specific FOVs is wide, median effective doses for FOVs in the range 5.1–10.0 cm are reduced 38% compared to >10 cm, and for FOV <5 cm are reduced 59% compared to FOVs with a height range of 5.1–10.0 cm (Al-Okshi et al. 2015). Similar FOVs including the lower jaw result in higher effective dose than those of the upper jaw because the salivary gland and thyroid tissues receive greater exposure (Lofthag-Hansen et al. 2011).

While reducing CBCT exposure and device parameters may result in dose reduction to the patient, there is often a concomitant decrease in image quality. Exposure parameters should be adjusted according to a specific clinical diagnostic task. Diagnostic tasks requiring high spatial and contrast detail and reduced noise (e.g., periapical diagnosis, assessment of possible ankyloses of impacted teeth, external and internal root resorption, assessment of peri-implant bone loss) (Lofthag-Hansen et al. 2011, Pinheiro et al. 2015) usually require higher exposures, the highest number of acquisition frames, complete arc trajectory, and smallest voxel as compared to less demanding clinical tasks (e.g., bone volume assessment associated with dental implant planning [Lofthag-Hansen et al. 2011]). CBCT imaging of regions with higher density, such as the mandible, may require higher exposure parameters compared to the maxilla (Lofthag-Hansen et al. 2011). Optimization of CBCT exposure parameters to provide acceptable diagnostic images can result in a dose saving of up to 50% (Hidalgo Rivas et al. 2015, Pauwels et al. 2017).

42.8.1.3 Patient and Personnel Protection

For operators of CBCT devices, additional shielding and personnel radiation dosimetry (radiation monitor badges) are desirable, but not considered necessary by all authorities, in CBCT facilities as isodose curves at one meter from CBCT units are reported to range from 2–40 µGy per scan (Holroyd and Walker 2010) compared with intraoral and panoramic radiography scatter doses of less than 1 µGy per exposure at one meter (Sutton and Williams 2000).

Recent authors have reported that the use of a lead torso apron does not reduce patient absorbed doses or effective dose in
panoramic (Rottke et al. 2013a,b) or CBCT (Rottke et al. 2017) procedures. However, the use of a thyroid collar reduces total effective dose, ranging from 9.8 to 22.7% for panoramic radiography (Han et al. 2013) and from 18 to 40.1% for CBCT imaging (Qu et al. 2012a). The use of thyroid collar in panoramic imaging is not advisable as it interferes with the projection geometry and introduces substantial artifacts.

### 42.8.1.4 Quality Assurance Procedures

Quality assurance (QA) refers to the principles, techniques, and clinical protocols adopted to ensure consistency in acceptable diagnostic image quality while maintaining radiation exposure to the patient as low as reasonably achievable (see Section III, Chapter 37). The regulations governing the implementation and monitoring of such a program vary greatly depending on country, and even regional jurisdiction, however generally include the following considerations (Holroyd and Walker 2010, Health Protection Agency 2010):

- **Installation assessment**: Because the exposure associated with CBCT devices is higher than other extraoral and intraoral dental radiographic systems, the facility room design and structural protection requirements may be greater to ensure adequate protection for both operator and others in areas adjacent to the unit.

- **Equipment performance**: Simple basic tests should be performed, both when the equipment is first installed (acceptance and commissioning tests) and then periodically (routine tests). These include X-ray tube output, voltage consistency and accuracy, filtration, exposure time, and radiation field collimation.

- **Patient dose**: When comparing specific MDCT devices, computed tomography dose index (CTDI), and dose length product (DLP) are relatively easy to assess and provide a metric for routine dose audit. However, for CBCT devices, these metrics do not provide a reliable dose quantity with good correlation to the effective dose and, therefore, patient risk. Dose area product (DAP) (Health Protection Agency 2010) and the CBCT dose index (European Commission 2012) have been proposed as more appropriate and clinically measurable indices of dose. Clinical DAP dose limits for adults and children have also been proposed as a method to establish diagnostic reference levels (DRL) by which devices can be compared for specific CBCT procedures. A DRL of 250 mGy cm² has been proposed for CBCT imaging for the placement of an upper first molar implant in a standard adult patient.

- **Image quality**: CBCT images must perform within acceptable clinical qualitative (e.g., comparison with high quality standard reference images) and quantitative (e.g., image density, contrast detail, uniformity, noise, spatial resolution, geometric accuracy, artifacts) parameters, such that adequate diagnostic information is achieved with minimal radiation exposure. Quantitative tests require specially devised phantoms, either provided by the manufacturer or available from a third party (e.g., Quart DVT_KP/DVY_150, Quart Zorneding, Germany; CBCT-161, Leeds Test Objects Ltd., Boroughbridge, United Kingdom)

- **Display screen performance**: Image quality is only as good as the monitor on which it is displayed. A suitable

<table>
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<tr>
<th>Clinical Application</th>
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test pattern, such as an AAPM TG18 or SMPTE image, should be displayed routinely to examine monitor spatial and contrast resolution (see Section IV, Chapters 63, 64 and 65).

### 42.9 Clinical Applications

CBCT is particularly suited for use in clinical dental practice, providing in-office high contrast volumetric imaging of the dental and maxillofacial regions at a relatively low dose. CBCT

**FIGURE 42.7** Volumetric rendering (a), reformatted panoramic image (b), and serial cross-sectional (c) cone beam computed tomography (CBCT) images of the maxilla of a teenager with multiple unerupted and impacted teeth and submerged deciduous (primary teeth), including the second premolars and right canine.

**FIGURE 42.8** A patient presented with pain and swelling of the maxillary right region. Conventional intraoral periapical image (a) in this area shows that all teeth are root canal filled teeth and the adjacent bone appears normal—note that the darker region above the roots of the teeth is the maxillary sinus. Sagittal (b) and axial (c) cone beam computed tomography (CBCT) images show a moderately sized periapical hypo-attenuating radiolucency associated with the buccal roots of the first molar, which is consistent with an acute infection. In addition, the CBCT images show lack of root canal filling of these roots, which was most likely the cause of the infection.

**FIGURE 42.9** Reformatted panoramic (a) and serial cross-sectional (b) cone beam computed tomography (CBCT) images showing severe root resorption of the left lateral incisor associated with the impacted and unerupted left canine.

**FIGURE 42.10** Reformatted panoramic image (a) and serial cross-sectional (b) cone beam computed tomography (CBCT) images of the mandible of a teenager with a single, round, well defined, homogeneously hyper-attenuating expansile mass in the left parasympyseal region displacing the unerupted canine to the midline. Biopsy confirmed the presence of an ossifying fibroma.

**FIGURE 42.11** An older patient presents with a gradually changing dental bite. Axial (a), coronal (b), and serial cross-sectional (c) cone beam computed tomography (CBCT) images of the left and right mandibular condyle show unilateral enlargement of the right condyle accounting for the shift in the patient’s occlusion. The provisional diagnosis of condylar chondroblastoma was confirmed with surgical excisional biopsy.
should be used when conventional dental imaging does not provide the information required for diagnosis and treatment planning (Carter et al. 2008). Table 42.4 lists, and Figures 42.7 through 42.17 provide illustrative examples of, clinical applications of maxillofacial CBCT in dentistry (European Commission 2012, Horner et al. 2015).

42.10 Summary

The continuing development and rapid commercialization of maxillofacial CBCT now provides both generalist and specialist dental practitioner access to accurate, sub-millimeter resolution imaging...
images in formats enabling volumetric visualization of the complexity of the maxillofacial region. All current generations of CBCT systems provide useful diagnostic images—future technical enhancements will most likely be directed towards reducing scan time, providing multimodal imaging, improving image fidelity, and incorporating task specific protocols to minimize patient dose. Increasing availability of this modality facilitates expanding maxillofacial imaging from diagnosis to image guidance of operative and surgical procedures.

REFERENCES


