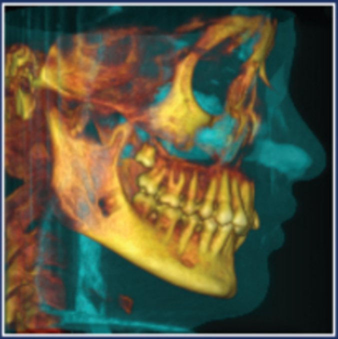

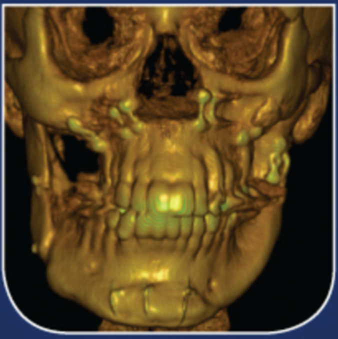

Cone Beam Computed Tomography in Orthodontics

INDICATIONS, INSIGHTS, AND INNOVATIONS

Sunil D. Kapila

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Cone Beam Computed Tomography in Orthodontics: Indications, Insights, and Innovations

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To my wife, Yvonne, and our children Anjuli, Sahil, and
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To my father, Dharam Inder, and late mother, Ved Kumari,
for their nurturing guidance and numerous sacrifices.

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Preface

Since its introduction to dentistry slightly over a decade ago, cone beam computed tomography (CBCT) has undergone a rapid evolution and considerable integration into orthodontics. However, despite the rapidly increasing popularity of CBCT and progress in applying it to clinical orthodontics, the profession has lacked a cohesive, comprehensive, and objective reference that provides clinicians with the background needed to utilize this technology optimally for treating their patients. Also, the specific indications and protocols for acquiring CBCT images and extracting appropriate clinical information have not been resolved fully. This textbook provides timely, impartial, and state-of-the-art information on the indications and protocols for CBCT imaging in orthodontics, clinical insights gained from these images, and innovations driven by these insights. As such, it is the most current and authoritative textbook on CBCT in orthodontics.

The book is organized to progress sequentially through specific topics so as to build the knowledgebase logically in this important and rapidly evolving field.

- **Part 1** on *Technology Assessment and Enhancements* provides the foundational information on CBCT technology, radiation exposure and risks, the transition from 2D to 3D imaging, and emerging technologies and future evolutions in computed tomography.
- **Part 2** contains chapters describing the *Protocols and Principles for CBCT Imaging in Orthodontics* that focus on developing evidence-based criteria for CBCT imaging, the medico-legal implications of CBCT to the professional, and the protocols and integration of this technology in orthodontic practice.
- **Part 3** provides critical information on CBCT-based *Diagnosis and Treatment Planning* that includes how to interpret CBCT scans and identify incidental pathologies, and the evolving discoveries and possible uses of CBCT to assess the temporomandibular joint, airway, and dentoalveolar boundary conditions.
- **Part 4** covers practical aspects of CBCT's *Clinical Applications and Treatment Outcomes* and encompasses a range of topics including root morphology and position, impacted and transposed teeth, rapid palatal expansion, outcomes with bone anchored maxillary protraction, temporary anchorage devices, virtual surgical treatment planning and outcomes, facial asymmetries, and craniofacial anomalies.

In reading the book, it will become evident that the insights gained from CBCT are contributing to novel or refined approaches to diagnosis, treatment, and biomechanics planning; assessment of treatment outcomes; and identifying opportunities for novel areas of research. Indeed, future evolutions in CBCT technology and improvements in the clinician's ability to extract and utilize clinically important information contained within the image dataset likely will lead to enhanced treatment outcomes and efficiencies in a broader spectrum of cases than currently possible.

The many authors who contributed to this book include recognized authorities in CBCT and 3D imaging, several of whom also have expertise in specific aspects of orthodontic treatment. They comprise oral maxillofacial radiologists, orthodontists, medical radiologists, engineers, oral and maxillofacial surgeons, and an oral pathologist. In addition to invited manuscripts from these experts, this volume includes chapters and videos of presentations given by well-known authorities in this field at the 39th Annual Moyers Symposium and the 38th Annual International Conference on Craniofacial Research (Presymposium). I believe that readers will find this book and accompanying DVDs a valuable resource for the appropriate and optimized application of CBCT to patient care and research.

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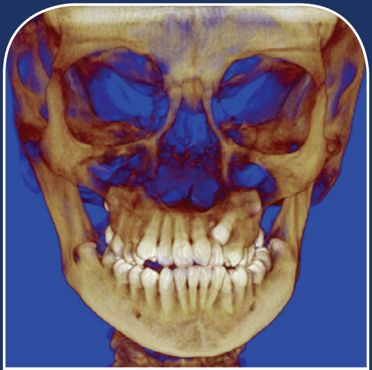
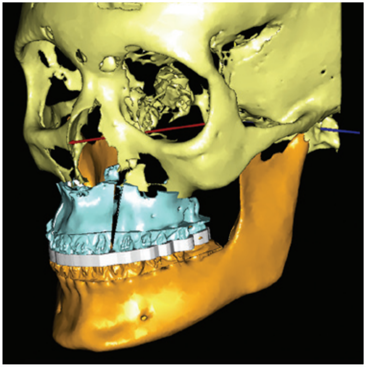
S.D.K.

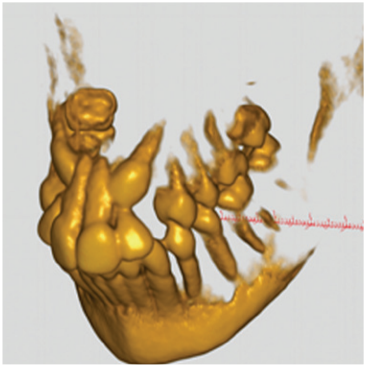
Cone Beam Computed Tomography in Orthodontics: Indications, Insights, and Innovations

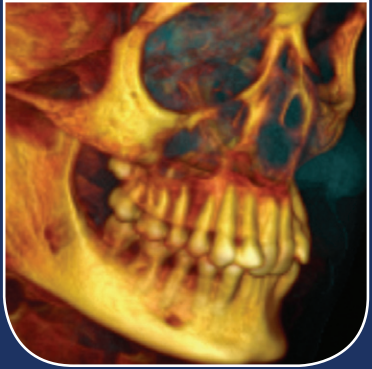


PART 1

Technology Assessment and Enhancements







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Contemporary Concepts of Cone Beam Computed Tomography in Orthodontics

Sunil D. Kapila, BDS, MS, PhD

INTRODUCTION

Truly transformative innovations are rare in most fields, but their emergence can generate a buzz that reverberates across disciplines. This is true especially in medicine and dentistry, which would stagnate without groundbreaking technologies that improve diagnosis, treatment planning, and prevention of disease. Among the advances in healthcare, radiological innovations are uniquely important as they have propelled advances in virtually most medical and dental specialties directly or indirectly. In this book, we examine how this technological cross-pollination works by detailing the broad impact of three-dimensional (3D) radiographic imaging on orthodontic diagnosis and treatment planning.

Several different technologies, including structured light, laser surface imaging, magnetic resonance imaging (MRI), computed tomography (CT), and cone beam computed tomography (CBCT), are currently available for 3D imaging. While these technologies differ in their operational details, all of them generate 3D images using the same general principles. In each of these imaging modalities, an emitted energy beam passing through or reflected from the body is modified by the structures that it encounters. A specialized sensor captures the modified energy beam, which then is converted into a 3D image by sophisticated software. Surface models, such as dental casts or slices through the 3D volume, which clearly display internal structures, can then be generated to improve diagnosis and treatment planning. Factors such as the desired image resolution, radiation exposure, soft tissue versus hard tissue visualization, and region of interest are used to determine which imaging modality is suited best for any given patient. Because of the need for orthodontists to image the craniofacial skeleton optimally and derive volumetric information, X-ray–based imaging is the best choice among these imaging technologies.

Cone Beam Computed Tomography in Orthodontics: Indications, Insights, and Innovations, First Edition. Sunil D. Kapila.

Within the volumetric 3D imaging subset, CBCT, as opposed to the more expensive CT or MRI or higher radiation CT technologies, currently is the most preferred approach for such imaging.

Since the introduction of CBCT to dentistry, which first was discussed comprehensively at the 2002 symposium “Craniofacial Imaging in the 21st Century” and documented in the proceedings of the meeting (Kapila & Farman, 2003), this technology has undergone a rapid evolution and considerable integration into orthodontics (Kapila *et al*., 2011). Typically the pattern of integration of a new technology into a discipline, such as CBCT’s utilization in dentistry, starts with early enthusiastic adopters who hope to extend the technology’s boundaries beyond its capabilities or utility, while others wait for evidence to justify the use of such technology and still others remain skeptical that the new technology will have any impact on their modality of practice, patient care, or treatment outcomes. Given the exponentially increasing research and clinical information on CBCT, it is likely that the latter group is dwindling as more clinicians begin to recognize the usefulness of CBCT, at least for patients presenting with specific clinical challenges. On the other end of the spectrum, the routine use of CBCT on every orthodontic patient remains a controversial issue since it is not clear that the information derived from CBCT enhances diagnosis or helps in modifying treatments in several case types, which is important particularly when weighed against the risks of radiation exposure.

This varied utilization of CBCT among clinicians exists within the context of research evidence, published case reports, or anecdotal observations on topics ranging from impacted teeth to temporomandibular joint (TMJ) morphology, many of which suggest that important information indeed can be obtained through CBCT imaging. Nevertheless, scientific evidence that the utilization of CBCT alters diagnosis and improves treatment plans or outcomes has only recently begun to emerge for some of its suggested applications. Also, for several of these recommendations in which the use of CBCT is logical and/or supported by scientific evidence, the specific indications for acquisition of CBCT images and protocols for imaging and extracting appropriate information have not been resolved fully. Finally, the information obtained from CBCT imaging requires a substantial level of expertise for interpretation that orthodontists currently may not have achieved (Ahmed *et al*., 2012), which has attendant medico-legal implications. Thus, despite the rapidly increasing popularity of CBCT and progress in understanding and applying it to clinical orthodontics, and possibly because of the large quantities of often disparate information on this imaging technology, a cohesive, comprehensive, and objective approach to its uses and advantages in orthodontic applications currently is lacking.

This textbook provides detailed, impartial, and state-of-the-art insights, indications, protocols, procedures, innovations, and medico-legal implications of CBCT. The insights gained from CBCT are contributing to novel or refined approaches to diagnosis, treatment, and biomechanic planning (Chapters 9–23), assessment of treatment outcomes (Chapters 12–15, 17, 19–23), and providing opportunities for novel areas of research (Chapters 4, 5, 12–23). These insights have been facilitated largely by the relative advantages of CBCT imaging over radiographic two-dimensional (2D) imaging.

This chapter provides an essential overview of the topics presented in this book with the goal of highlighting the current knowledge on CBCT technology, its applications in defining 3D craniofacial anatomy and treatment outcomes, incidental findings and their medico-legal implications, and evidence-based indications and protocols for clinical applications of CBCT. In reading this chapter and book, it will become apparent that while some applications and areas have advanced sufficiently with demonstrated scientific evidence for the efficacy of CBCT in enhancing diagnosis and treatment planning, the use of CBCT in other clinical situations still is evolving. Thus, depending on where this field is in specific types of cases, the topics may range from current science to implied clinical applications to actual utility in patients who present with specific clinical findings. It is likely that as the field advances and more evidence of the efficacy of CBCT emerges, its applications in orthodontics will increase or be modified. This will enable clinicians to realize the ultimate goal of increased treatment efficiency or outcomes or both in many more clinical scenarios.

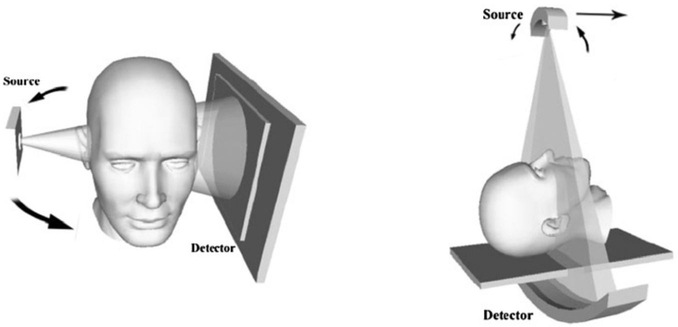
EVOLUTION IN AND BASICS OF CBCT TECHNOLOGY

CBCT technology owes its inception to the discovery of X-rays by the physicist Wilhelm Conrad Röntgen in 1895, which enabled the first ever non-invasive visualization inside the human body. The discovery of X-rays was a landmark achievement in the medical field and contributed to innovative changes in how medicine and surgery are practiced. Since its initial discovery, radiographic imaging has found widespread applications in many healthcare fields. Although the images derived from the original planar X-ray technology have proven to be valuable diagnostically, they are 2D images of 3D objects, which have inherent caveats and considerable loss of information that could be of value in clinical practice or in research discoveries. Other limitations of 2D radiographic imaging include magnification, geometric distortion, superimposition of structures, projective displacements (which may elongate or foreshorten an object's perceived dimensions), rotational errors, and linear projective transformation (Tsao *et al*., 1983; Quintero *et al*., 1999; Adams *et al*., 2004).

The subsequent exponential advances in computer hardware and software technologies and electrical engineering resulted in the next significant breakthrough in radiography, namely, the development of CT independently by Hounsfield and Cormack in the early 1970s (Raju, 1999; Oransky, 2004). This technological advancement enabled the generation of 3D images and the ability to view an object in its entirety from all possible viewpoints. The advantages of CT relative to 2D radiography resulted in its rapid adoption in many medical and dental fields. Successive enhancements in CT technology attributable to improvements in hardware have resulted in units with faster scanning times and relatively high image quality. In the two decades following the introduction of CT, the spiral or helical CT in effect became the standard instrument for medical imaging, which was supplanted by the multislice CT (MSCT) or multirow detector CT (MDCT) in 1998. Although medical CT has been used for craniofacial imaging from its earliest days, its utilization for this purpose increased only when high-resolution scanners with slice thicknesses of 2 mm were developed in the 1980s (Mozzo *et al*., 1998). However, due to the high levels of radiation, cost of the imaging units, and inaccessibility, use of medical CT for craniofacial imaging generally has been limited to patients for whom the risk-benefit ratio was considered favorable, such as for those with craniofacial anomalies, trauma, or cancer.

CBCT scanners were developed for craniofacial imaging in the late 1990s, in part to overcome several of the limitations of MSCT. In 2001, the Food and Drug Administration (FDA) approved CBCT scanners for sale in the United States, which led to their introduction into dentistry that year. CBCT differs from MSCT in the shape of the beam, the configuration of the detectors, and the software algorithms used to reconstruct the images (Figure 1.1; see also Chapter 2). These hardware and software modifications enable CBCT to capture images of the desired region of interest (ROI) with only one or two rotations, thereby decreasing the radiation exposure and time required to scan the patient compared with MSCT scans. Another advantage of CBCT scanners is their availability as compact and relatively inexpensive units that can be installed in private clinics, including those of general dentists, oral surgeons, and orthodontists (Vannier, 2003). The growing popularity and use of CBCT is evident by the more than 40 different CBCT units that now are available from more than 20 manufacturers (Molen, 2011; see also Chapters 2, 4, and 6). It is apparent that the development and availability of these specialized low-radiation-dose CBCT scanners for imaging craniofacial structures has driven the adoption and integration of 3D digital imaging into dentistry and increasingly is becoming an important source of 3D volumetric data supplemented with 2D multiplanar reconstructions (MPR; Figure 1.2) in clinical orthodontics.

Historically, 2D imaging, including traditional radiographs and photographs, combined with 3D data obtained from models and clinic examination, has been a mainstay of orthodontic diagnosis and treatment planning. In contrast, in cases where indicated, the acquisition of clinical information entirely from 3D imaging, including CBCT, would allow for the evaluation and analysis of the true anatomy providing clinically accurate 3D representations of craniofacial structures, teeth, and



- Cone shaped x-ray beam
- Flat panel detector
- Only one or two 360 degree rotations
- Low radiation dose
- Volumetric data set

A

- 2D fan shaped x-ray beam
- Several rows of circular detector arrays
- Hundreds of rotations
- High radiation dose
- Dataset comprised of 2D slices

B

Figure 1.1 Diagrammatic representation of CBCT (*A*) and MSCT (*B*) units and summary of key differences between these two types of CT imaging modalities. (Modified and reprinted with permission from Miracle & Mukherji, 2009.)

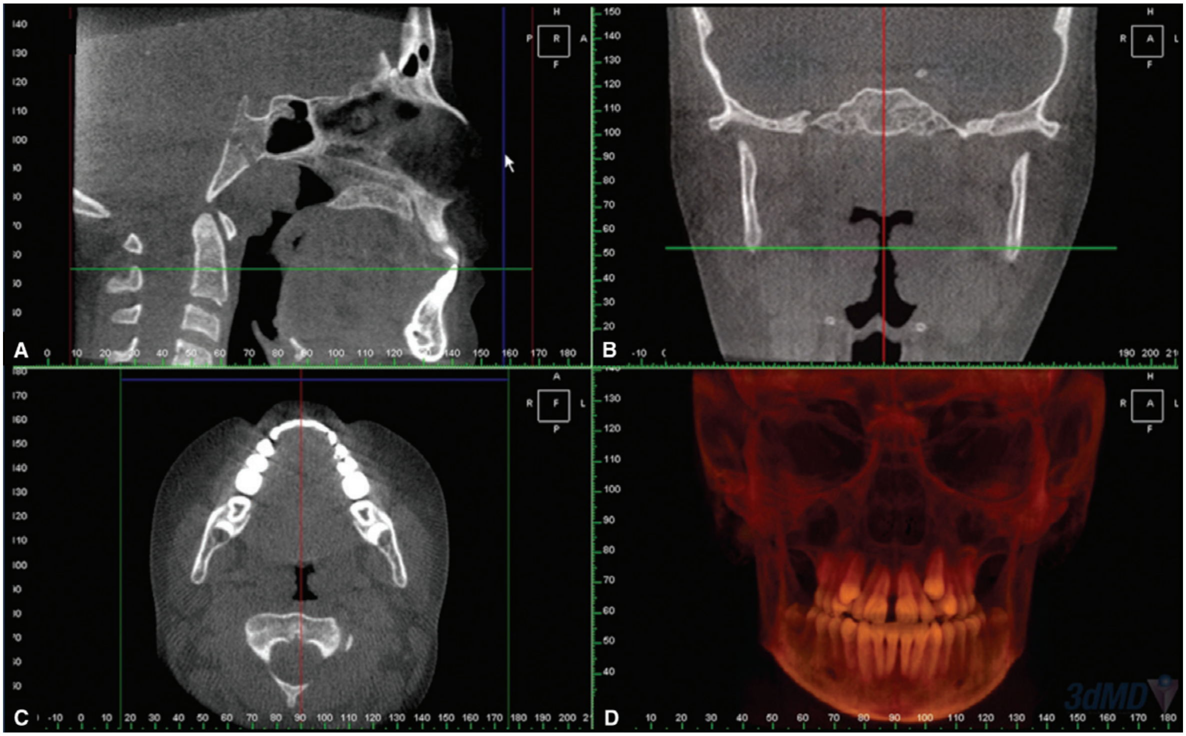


Figure 1.2 CBCTs provide multidimensional perspectives, including 2D cross-sections in the sagittal (*A*), coronal (*B*), and axial (*C*) planes. The image can be scanned through slice planes to reveal details of the anatomy in any of the three planes of space. The 3D volumetric-rendered view (*D*) can be rotated in all three planes of space to reveal the anatomic structures, their relationships, and the volumes of the dental, skeletal, and airway anatomy. In this case, the sagittal, axial, and coronal views reveal enlarged adenoids and tonsils. A narrow and asymmetric maxilla that is rotated to the patient's right and impacted maxillary canines is noticeable in the rendered view.

roots with no superimposition of structures. Unlike several other 3D imaging methods (e.g., structured light or surface laser scanning), CBCT imaging, in addition to providing acceptable representation of soft tissue surface anatomy, has the advantage over most other 3D imaging modalities of incorporating details of underlying skeletal and dental structures, albeit with the caveat that the patient is exposed to radiation.

The pace of CBCT innovations and applications to orthodontics is reflected by the rapidly expanding numbers and quality of publications on this topic. A PubMed search using the key words CBCT or cone beam computed tomography and orthodontics generated 558 references published in English up to the end of 2013. These include three published in 2003, none in 2004, five each in 2005 and 2006, 14 in 2007, 18 in 2008, 55 in 2009, 71 in 2010, 98 in 2011, 132 in 2012, and 157 in 2013. Of these publications, a substantial subset are original or research studies that can be classified broadly into the following categories: (1) technology assessment and enhancements, (2) craniofacial and airway morphometric analyses in health and disease, (3) CBCT use in analyzing treatment outcomes, (4) incidental findings and medico-legal implications, and (5) evidence-based indications, uses, and efficacy of CBCT in diagnosis and treatment planning, all of which are discussed in greater depth in the remainder of this chapter.

TECHNOLOGY ASSESSMENT AND ENHANCEMENTS

Technology assessment studies that include radiation exposure, accuracy of measurements and images, comparison of 3D with 2D images, and advances in software and hardware technologies provide important information needed for the effective and safe utilization of CBCT.

Radiation exposure

Radiation exposure is determined by several variables, including the type of unit used, field of exposure, pulsed versus continuous exposure, milliamperage seconds (mAs), peak kilovoltage (kVp), beam filtration, and number basis of images, several of which can be controlled by the technician or clinician. A wide variation in radiation exposure has been reported for different CBCT units (Brooks, 2009; see also Chapters 2 and 3). The field of view (FOV)-dependent effective dose of CBCT varies: 68–1074 μSv for large (>15 cm), 69–560 μSv for medium (10–15 cm), and 189–652 μSv for small (8–10 cm) FOV (Silva *et al*., 2008; Ludlow, 2009a, 2009b; also see Chapter 3). The effective dose for a craniofacial (large or extended) FOV CBCT scan ranges from 114 to 282 μSv when using a 10-year-old phantom and from approximately 81 to 216 μSv effective dose when using an adolescent phantom (Theodorakou *et al*., 2012). In contrast, although MSCT provides better soft tissue visualization than CBCT, it has a higher radiation dose of 280–1410 μSv for a maxilla-mandibular image (Loubele *et al*., 2005; Garcia Silva *et al*., 2008a; Okano *et al*., 2009; Suomalainen *et al*., 2009) and generates greater scatter from metal restorations than CBCT, which impacts the quality of the image (Farman & Scarfe, 2006; see also Chapters 2 and 3). Thus, relative to MSCT, CBCT provides appropriate levels of detail at a substantially reduced radiation exposure.

Radiation exposure is an important factor when considering whether to take a CBCT or conventional 2D radiographs. Compared with conventional 2D orthodontic radiographic series of a panoramic radiograph (2.7–24.3 μSv), a lateral cephalogram (<6 μSv) and a full-mouth series (<1.5 μSv per radiograph, or approximately 27 μSv for 18 radiographs; Garcia Silva *et al*., 2008a, 2008b; Ludlow *et al*., 2008; Ludlow & Ivanovic, 2008; Palomo *et al*., 2008; Okano *et al*., 2009), CBCT radiation exposure can be equivalent to or greater than traditional imaging depending on the FOV and age of the patient (Silva *et al*., 2008; SEDENTEXCT, 2011; also see Chapter 3). More specifically, when comparing radiation exposure for the large or extended FOV CBCT preferred by those clinicians who undertake CBCT in lieu of the standard orthodontic imaging, the CBCT radiation exposure derived using an adolescent or child phantom is approximately two- to tenfold greater than the combined effective radiation dose of approximately 30 μSv from a cephalogram and panoramic radiograph (Table 1.1). The use of

Table 1.1 Comparison of effective radiation doses from conventional 2D radiography, CBCTs using pediatric phantoms for dentoalveolar (small and medium) and craniofacial (large) FOVs, MSCT, and background radiation. Most of the radiation data are provided in ranges and medians (in parentheses).

Type of radiography	Specific radiograph or methods	Effective dose (μSv)
2D radiography	Intraoral (PAs and bitewings) Panoramic Cephalometric	27 2.7–24.3 <6
Dentoalveolar FOV CBCT	10-year-old phantom	16–214 (43)
	Adolescent phantom	18–70 (32)
Craniofacial FOV CBCT	10-year-old phantom	114–282 (186)
	Adolescent phantom	81–216 (135)
Conventional CT	MSCT	280–1410
Background radiation		8

Sources of data include Loubele *et al.*, 2005; Garcia Silva *et al.*, 2008a, 2008b; Ludlow *et al.*, 2008; Okano *et al.*, 2009; Palomo *et al.*, 2008; Theodorakou *et al.*, 2012.

Table 1.2 Radiation risk in relation to age. This approach assumes a multiplicative risk projection model averaged for the two sexes. In fact, the risk for females always is higher relatively than for males.

Age group (years)	Multiplication factor for risk
<10	×3
10–20	×2
20–30	×1.5
30–50	×0.5
50–80	×0.3
80+	Negligible risk

Data are derived from ICRP (1991) and represent relative attributable lifetime risk standardized to the relative risk of 1 at age 30, which is considered the population average risk. (Reprinted with permission from SEDENTEXCT, 2009.)

a dentoalveolar FOV CBCT where indicated combined with a cephalometric radiograph also has a lower effective radiation exposure than a craniofacial FOV, although this difference in radiation exposure is much less marked than when comparing the traditional 2D radiographic series with a large or extended FOV CBCT. Another approach for understanding the potential effects of radiation exposure from radiographic imaging is to compare this exposure with that from background radiation. Given that the background radiation in the United States is approximately 8 μSv per day, a large FOV would expose the patient to an equivalent of 10 to 35 days of background radiation.

A final consideration for radiation risks, particularly for orthodontic patients, most of whom are children or adolescents, is *attributable lifetime radiation risk* (ICRP, 1991, 2008). This determination is based on the assumption that younger subjects are at a higher risk to the adverse effects of radiation exposure over their lifetimes than are older patients because of their length of remaining life, greater proportion of mitotic cells, and lower radiation resistance of tissues. Table 1.2 summarizes the age-related lifetime radiation risk multiplication factor based on a relative risk of one at age 30 years, which is used as the population average risk. These data show that relative to the risk of radiation exposure to a 30-year-old, children less than 10 years old have a three-fold greater radiation risk and those between 10 and 20 years have a two-fold greater attributable radiation risk; this suggests that extra caution should be exercised prior to exposing children and young adults to radiographic examination.

Overall, irrespective of the patient's age, it is important to weigh the risks of radiation exposure against the expected clinical benefits of imaging, given the possible sequelae of exposure to radiation (see also Chapters 3 and 6). The latter determination is based on an objective assessment of whether any additional information obtained from these scans is likely to enhance diagnosis and/or treatment planning prior to taking CBCT imaging. Conversely, it should be emphasized that radiation risks alone are not an adequate reason for not taking a CBCT scan when indicated. Instead, knowledge of radiation exposure and risks should be used to make informed decisions on when CBCT could prove to be beneficial for extracting additional diagnostic information and/or providing optimal treatment to the patient. Finally, when deciding on undertaking radiographic imaging it is important to exercise the "As Low As Reasonably Achievable" (ALARA) principle (Farman & Scarfe, 2006).

Accuracy of CBCT-derived cephalograms and measurements versus gold standard

Studies have also been performed to determine the translatability and utility of CBCT relative to the most commonly used current methods of morphologic assessment, namely, cephalometrics and panoramic radiographs. Techniques for reconstructing cephalograms from CBCT have been developed (Farman & Scarfe, 2006) and measurements from these reconstructions can be compared directly with measurements from traditional cephalograms to assess their accuracy (Kumar *et al.*, 2008). Such studies have revealed no significant differences in linear and angular measurements from cephalograms reconstructed from the NewTom 3G CBCT (NewTom Germany AG, Marburg, Germany) relative to conventional 2D cephalograms (Kumar *et al.*, 2008). While these comparisons provide important information, it probably is more important to determine the accuracy of measurements from CBCT surface-rendered volumetric images to direct "gold standard" anatomical measurements made on the object of interest. Findings from studies on this subject have shown that the mean percentage measurement error for 3D CBCT is higher significantly (2.3%) than replicate skull measurements (0.6%; Periago *et al.*, 2008). Additionally, most of the midsagittal 3D CBCT measurements were smaller systematically and significantly when using Dolphin 3D (Dolphin Imaging and Management Systems, Chatsworth, CA) software than those made directly from the skull, reflecting some potential need for image correction algorithms in the software. Similar but smaller systematic differences in 3D CBCT measurements made using NewTom HQR DVT 9000 and Hitachi MercuRay (Hitachi Medical Corp, Tokyo, Japan) versus true measurements on the skull have been reported by others (Stratemann *et al.*, 2008). Fortunately, the majority of measurements from 3D CBCT were within 2 mm of those made directly from the skull, indicating that while the differences may be significant statistically for research purposes, they may not be relevant clinically.

As pointed out in several chapters, the direct comparison of cephalograpms with CBCT imaging may be a transitional step in the adoption of this new technology into the field. Novel approaches currently are being devised for 3D analyses and superimpositions for assessment of treatment outcomes (Chapters 19 and 21), monitoring disease progression and responses to therapy (Chapter 12), and research purposes (Chapter 4) that likely will result in the traditional 2D analyses methods becoming less relevant in specific case types and in research in orthodontics.

Comparison of CBCT versus panoramic radiograph

Qualitative assessments also have been made to determine whether CBCT images provide more detailed information than routine orthopantomograms or panoramic radiographs in various orthodontically relevant situations. A subjective comparison of reconstructed panoramic images from two CBCT units (NewTom 9000 and Arcadis Orbic 3D; Siemens Medical Solutions, Erlangen, Germany) with routine panoramic projection demonstrated a gain in information over conventional radiography for localizing impacted and retained teeth, the presence or absence of root resorption, cleft lip and palate (CL/P), and third molar evaluation, but not for changes in the TMJ (Korbmacher *et al.*, 2007). Other studies have shown that CBCT provides a more accurate assessment of root parallelism, root resorption, and localization of impacted teeth than do panoramic or other 2D radiographs (Peck *et al.*, 2007; Alqerban *et al.*, 2009a, 2009b, 2011a, 2011b; Van Elslande *et al.*, 2010; Bouwens *et al.*, 2011; Durack *et al.*, 2011; Ponder *et al.*, 2012; Ren *et al.*, 2012; see also later and Chapters 15 and 16).

Technology enhancements

As described in Chapters 2, 4, 5, 20, and 21, CBCT hardware and software technologies continue to undergo rapid evolution and enhancement. Indeed, CBCT units now are available with varied configurations that include adjustable or even customizable FOVs. Other discoveries and improvements in X-ray source technologies, detectors, and post-processing of images will offer further opportunities for reduction in radiation and customization of imaging protocols. Additional developments in software include introduction of user-friendly treatment planning software and the increasing automation in 3D superimposition that will be of utility in both clinical and research applications. Progress also is being made in applying new methodologies that facilitate the merging of 3D datasets from different sources and in verifying the efficacy of these enhancements in clinical decision-making. A key extension in the utility of 3D imaging involves rapid progress in technologies such as 3D printing that increasingly are becoming available for fabrication of surgical splints and specialized orthodontic appliances that also have substantial yet untapped practical applications (see also Chapter 20).

CBCT MORPHOMETRIC ANALYSES IN HEALTH AND DISEASE

CBCT-based 3D craniofacial and dental morphometrics is important for defining normal and abnormal 3D anatomy of structures with a potential for longer-term utility in diagnosis and treatment planning. Much work to date on this topic has focused on quantitative and qualitative determinations of the morphology of craniofacial structures, airway, TMJ, roots, and dentoalveolar boundary conditions.

Qualitative and quantitative assessments of craniofacial morphometrics

3D imaging allows for analysis of normal size, shape, and volume of various craniofacial structures and facilitates the determination of differences in these variables between bilateral structures (Stratemann *et al*., 2010). Although CBCT has the potential for defining craniofacial growth changes in 3D, its sole use for this purpose is highly unlikely due to radiation concerns. To date, three main methods have been utilized for analyzing 3D anatomy and changes due to treatment in craniofacial structures. The first method extends approaches that are utilized in 2D cephalometry to derive linear and angular measurements from 3D images (Jung *et al*., 2009; Kim *et al*., 2010, 2011). This approach has the caveat of reducing 3D dimensions into 2D measurements. The second method, called Closest Point analysis (Figure 12.8 and Figure 12.9B) determines the smallest displacements between two structures but does not account for changes in shape (Cevidanes *et al*., 2007; Almeida *et al*., 2011; Motta *et al*., 2011). Shape correspondence (Figure 12.9B) is the third method that determines the displacement of a given landmark between two time points and represents these as either vectors or color-coded maps to depict the directionality and amount of movements, respectively (Paniagua *et al*., 2010; see also Chapters 12, 19, and 22). In the future, it is likely that the latter and similar approaches will replace or complement linear and angular measurements made from 3D or planar reconstructions for determining treatment changes from CBCT images.

Root morphology, resorption, and angulations

Root length, form, and resorption traditionally have been assessed via periapical radiographs, while post-orthodontic root parallelism and relationships customarily are determined using panoramic radiographs. Recent studies show that CBCT provides enhanced visualization of roots, making it a valuable tool for assessing pre- or post-orthodontic root resorption and parallelism. Using true anatomic root and tooth length as a gold standard, it has been shown that CBCT is at least as good as periapical radiography for assessing root and tooth length (Lund *et al*., 2010; Sherrard *et al*., 2010). Because of its ability to generate precise images of small root defects,