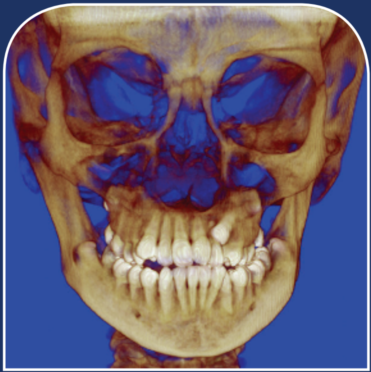
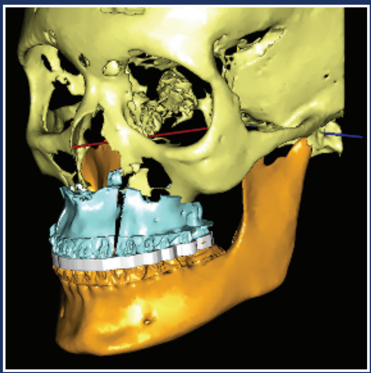
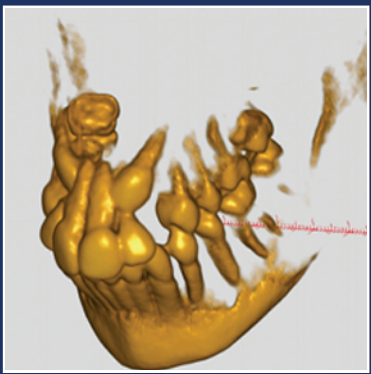
Cone Beam Computed Tomography in Orthodontics: Indications, Insights, and Innovations







PART 1

Technology Assessment and Enhancements

1 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

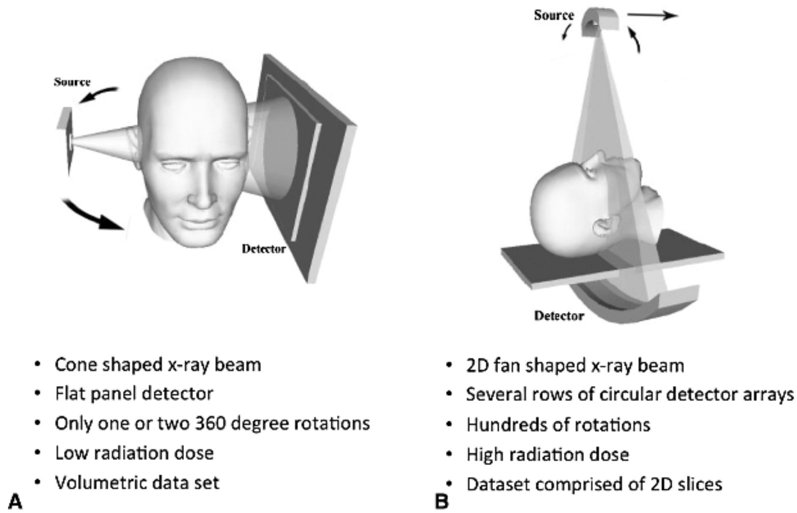


Figure 1.1 Diagrammatic representation of CBCT (*A*) and MSCT (*B*) units and summary of key differences between these two types of CT imaging modalities. (Modified and reprinted with permission from Miracle & Mukherji, 2009.)

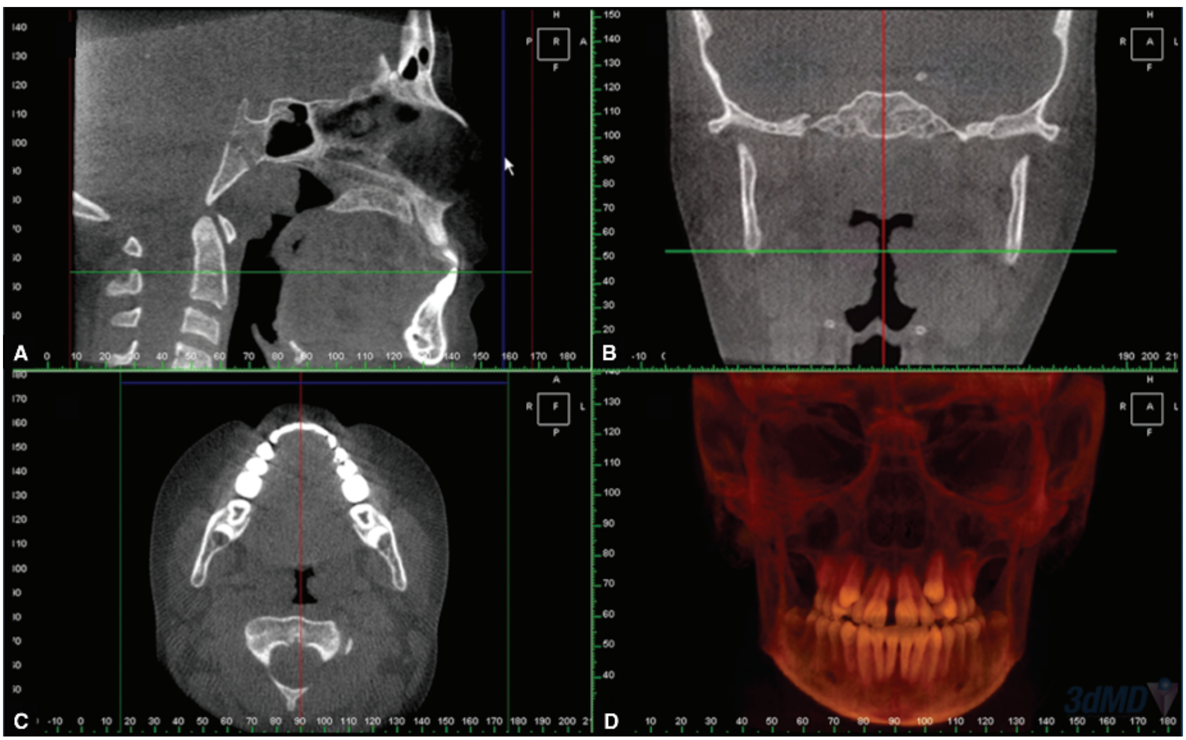


Figure 1.2 CBCTs provide multidimensional perspectives, including 2D cross-sections in the sagittal (*A*), coronal (*B*), and axial (*C*) planes. The image can be scanned through slice planes to reveal details of the anatomy in any of the three planes of space. The 3D volumetric-rendered view (*D*) can 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)	27
	Panoramic	2.7–24.3
	Cephalometric	<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, CBCT provides more accurate insights into root resorption as well as greater sensitivity and specificity in detecting these lesions than do panoramic or other 2D radiographs (Alqerban *et al*., 2009a, 2009b, 2011; Durack *et al*., 2011; Ponder *et al*., 2012; Ren *et al*., 2012). Also relative to CBCT, panoramic radiographs underestimate external apical root resorption (EARR; Segal *et al*., 2004; Dudic *et al*., 2009) such that *in vivo* root resorption is diagnosed on 43% of all teeth on panoramic radiographs compared with 69% of all teeth on the CBCT images (Dudic *et al*., 2009). For maxillary incisors, root resorption is not diagnosed 20% of the time with panoramic radiographs and 14% of the time with CBCT images. Finally, while 2D radiographs provide visualization of only the apex and the mesial and distal root surfaces, CBCT imaging adds insights into the effects of treatment on buccal and lingual root surfaces. This has led to the novel discovery that root loss not only is present at the root apex or is symmetrical around the root surface, but also shows a slanting pattern on surfaces adjacent to the direction of tooth movement. This finding highlights the efficacy of CBCT's 3D rendering capacity for accurate diagnosis of both EARR and other types of root resorption.

Since root parallelism is an important goal of orthodontic treatment, its accurate determination could add valuable information in assessing the quality of treatment outcomes and, possibly, of post-treatment stability. Several studies show that panoramic radiographs generate numerous errors in the assessment of root angulation. Specifically relative to true angulations, the roots of maxillary anterior teeth often appear tipped mesially, while posterior teeth appear inclined distally, and roots of all mandibular teeth appear tipped more mesially on panoramic radiographs (McKee *et al*., 2002; Garcia-Figueroa *et al*., 2008; Owens & Johal, 2008). Recent studies comparing gold standard direct measurements on typodonts or skulls demonstrate that CBCT images, though not perfect, provide improved angular measurements relative to those derived from 2D radiographs (Peck *et al*., 2007; Van Elslande *et al*., 2010; Bouwens *et al*., 2011). Despite these findings, the assessment of root parallelism currently does not qualify as an indication for CBCT imaging.

Bone quality and quantity assessments

Evaluating the status of the alveolar housing or boundary conditions is gaining increasing importance as a component of orthodontic patient evaluation (see also Chapter 14). For example, changes in bone height and width measurements increasingly are being utilized for assessing orthodontic treatment outcomes (Garrett *et al*., 2008; Kartalian *et al*., 2010; Tai *et al*., 2010a; Cattaneo *et al*., 2011; Corbridge *et al*., 2011; see also Chapter 14). Although dentoalveolar bone morphology and its relationship to underlying roots is an important component of orthodontic diagnosis and treatment, some controversy remains on the accuracy, reliability, and reproducibility of CBCT in assessing bone morphology, quantity, and quality. The accuracy of bone width dimensions depends on CBCT machine-specific settings including mAs, kVp, exposure time, and sensor size, and patient-specific variables including age, bone density, and periodontal biotype (Molen, 2010). Studies have shown that bone width particularly above a specific bone thickness threshold can be determined from CBCT with a relatively high level of reliability and reproducibility and, therefore, accuracy (Leung *et al*., 2010; Patcas *et al*., 2012). Although CBCT provides accurate assessment of alveolar bone height, caution must be exercised in evaluating fenestrations due to the high number of false positives in the determination of these defects (Leung *et al*., 2010; Patcas *et al*., 2012).

Both the quantity and quality of the cortical bone and the quality of underlying trabecular bone may be important in determining primary stability of temporary anchorage devices (TADs), which, in turn, is relevant to secondary TAD stability over the longer term (Dalstra *et al*., 2004; Wilmes *et al*., 2006; Marquezan *et al*., 2012; see also Chapter 18). Bone density often serves as a surrogate for bone quality and typically is measured using Hounsfield Units (HU)—a method previously devised for MSCT. HU measurements allow clinicians to assess the health of tissues. For example, alveolar bone density at a proposed dental implant site can be measured with MSCT prior to surgery to determine whether the density is sufficient to support the implant or whether a bone graft should be performed first. The HU scale assigns unit values to air, soft tissues, water, and hard tissues based on their ability to attenuate an X-ray beam. On the HU scale, air has an HU value of −1000, water is 0, and dense bone is ≥+1000. Soft tissues, which have high water content, have HU values that fall between water and dense bone. Because all conventional CT machines are calibrated to ensure that the grayscale measurements on each scan are accurate, all HU measurements taken on conventional CT-generated images can be compared directly with each other. In contrast to MSCT, because the grayscale on CBCT images is not calibrated, this technology cannot be used to measure bone density accurately; in fact, it is arbitrary, which means that tissue densities on two CBCT scans, even if taken on the same patient, cannot be measured or compared directly (Katsumata *et al*., 2006, 2007; Swennen & Schutyser, 2006). Thus, while a CBCT image can be used to determine if an edentulous site has sufficient alveolar bone thickness to support a dental implant, it cannot be used to determine if the bone density is sufficient to withstand the surgical placement and long-term functional stresses of implant treatment. Efforts are ongoing to develop algorithms that convert specific parameters, such as a voxel volume (VV) grayscale, derived from CBCT to quantify bone density.

TMJ anatomy and morphology

Although little information currently is available on the efficacy of CBCT in enhancing the diagnosis of TMJ disorders over routine radiography, CBCT has been shown to be more efficacious than conventional tomography and MRI in detecting osseous changes (Honey *et al*., 2007; Alkhader *et al*., 2010). Comparison of asymptomatic control and osteoarthritic TMJs by shape correspondence also has shown significant differences between the morphologies of healthy and degenerative condyles (Cevidanes *et al*., 2010a). This study also revealed a significant correlation of both pain intensity and pain duration with the variations in 3D morphology of the osteoarthritic condyles. While these findings suggest the potential utility of CBCT as a diagnostic aid in TMJ osteoarthritis (OA), it is important to understand that structural bony changes of the TMJ alone do not reveal whether or not the disease is active, and no direct correlation between TMJ morphological changes and clinical findings in OA or other arthritides exists.

Airway morphology and relationship to obstructive sleep apnea (OSA)

As reported later in this book (see Chapter 13) and in a recent publication (Schendel & Hatcher, 2010), CBCT can be used to image the airway accurately to provide cross-sectional area, minimum cross-section, and total airway volume (Figure 1.3). Initial investigations on airway patency, function, and disorders utilizing CBCT have provided preliminary answers including dimensions of normal airway anatomy in adults (Smith, 2009),

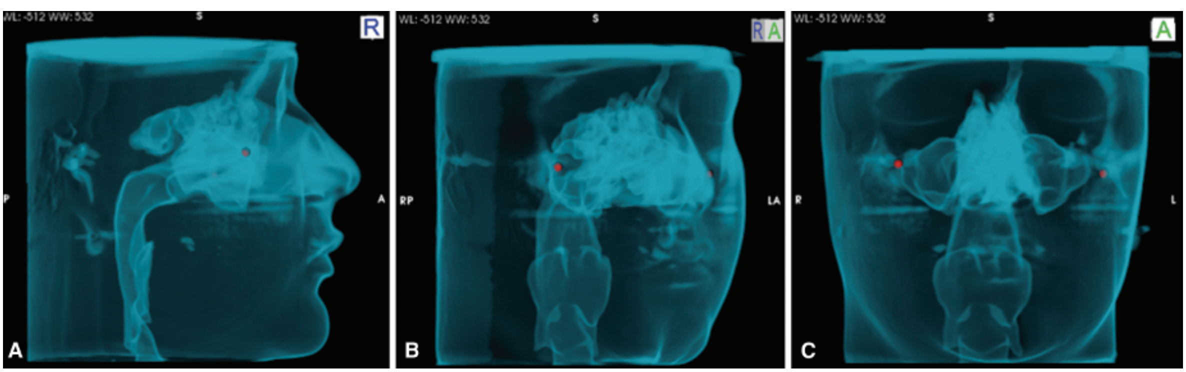


Figure 1.3 3D airway visualization in the lateral (*A*), three-quarter (*B*), and frontal (*C*) views. Both qualitative and quantitative assessments of the airway can be made by thresholding specific tissue density either through features built into the software program, as performed here, or by customized selection of a window of density to obtain refined and accurate 3D volumetric, cross-sectional area, and linear measurements of the airway.

relationship of 2D to 3D measurements (Lenza *et al*., 2010), differences in airway morphology in obstructive sleep apnea (OSA) and non-OSA subjects (Haponik *et al*., 1983; Galvin *et al*., 1989; Avrahami & Englender, 1995; Caballero *et al*., 1998; Schwab *et al*., 2003; Yucel *et al*., 2005), and the effects of rapid palatal expansion (RPE) and orthognathic surgery on airway dimensions (Samman *et al*., 1992; Chen *et al*., 2007; Degerliyurt *et al*., 2008; Oliviera de Felippe *et al*., 2008; Hong *et al*., 2011; see also Chapters 13, 17, and 22). Several of these studies show no relationship between 2D linear and 3D cross-sectional areas of airway, which suggests that the use of 2D data may not be valid for assessing airway patency. Also up to this time, no studies have demonstrated that qualitative or quantitative assessments of CBCT are capable of predicting OSA accurately.

UTILITY OF CBCT IN ASSESSING TREATMENT OUTCOMES

Because CBCT is 3D and not subject to the error and overlap found in lateral or posterior-anterior cephalometry, it provides the capability of assessing treatment outcomes in all three planes of space as well as volumetrically. As a result of these advantages over routine radiography, CBCT is becoming an important tool in assessing outcomes of orthodontic and surgical therapies. These include the determination of the effects of treatments on orthopedic versus orthodontic changes, root resorption, bone boundary conditions, airway, alveolar grafting in CL/P, and orthognathic surgery as discussed later and in Chapters 12, 14, 15, and 17–23.

Maxillary expansion

CBCT has enabled more in-depth dissection of responses of bone and teeth to maxillary expansion than was possible through 2D radiography or study models. For example, studies on four-banded maxillary expanders have revealed that although the first premolar, second premolar, and first molar all have similar magnitudes of total overall expansion (which includes skeletal expansion, dental tipping, and alveolar bone bending), the skeletal expansion is greater in the anterior than posterior maxilla (Rungcharassaeng *et al*., 2007; Garrett *et al*., 2008; Kartalian *et al*., 2010). These differences in findings between skeletal and overall expansion result from increasingly greater alveolar bone bending and the buccal crown tip going back from the first premolar to the first molar. Of the total expansion obtained in one of these studies with an adolescent sample (mean age 13.8 ± 1.7 years), 38% was orthopedic, 13% was due to alveolar bending, and 49% resulted from dental tipping (Garrett *et al*., 2008). These studies confirm that besides sutural expansion, RPE produces both dental and alveolar tipping, and suggest that much of post-expansion relapse probably occurs from "rebound" from the alveolar bending and dental tipping, since these two modalities of expansion are hard to retain. Additionally, the sample showed an increase in nasal width and decrease in maxillary sinus width (Garrett *et al*., 2008). In contrast to expansion using the fixed RPE appliance, a removable Schwarz appliance achieves expansion in both arches through alveolar buccal tipping (Tai *et al*., 2010a, 2010b).

Treatment effects on alveolar boundary conditions

Alveolar boundary conditions are the depth, height, and morphology of alveolar bone relative to tooth root dimensions, angulation, and spatial position (Kapila *et al*., 2011; see also Chapter 14). Boundary conditions are determined not only by dentoalveolar anatomy prior to treatment, but also by the bone's adaptability during tooth movement and its morphology following the final positioning of teeth. Thus, in the context of orthodontic tooth movement, boundary conditions can be considered to be dynamic and dependent on the patient's pre-treatment bone and gingival biotype as well as bone physiology. This implies that pre-treatment status of alveolar boundary conditions and their potential adaptation may dictate the limits of both the planned tooth movement and the final desired spatial position and angulation of the tooth.

The effect of orthodontic treatment and various appliances on bone morphology and boundary conditions in three planes of space can be assessed relatively well with CBCT, though not perfectly due to some of its technological limitations (see earlier and Chapter 14). This approach has been used to discern the potential effects of treatment- or patient-specific variables on the integrity and morphology of bone around tooth roots in full-fixed appliance therapy and with both rapid and slow expansion (Rungcharassaeng *et al*., 2007; Garrett *et al*., 2008; Kartalian *et al*., 2010; Tai *et al*., 2010a; Cattaneo *et al*., 2011; Corbridge *et al*., 2011; Johnson, 2011; Welmerink, 2012). Thus, it has been shown that routine orthodontic therapy using full-fixed appliances is accompanied by significant changes in bone width even with small amounts of buccal movement of posterior teeth (Johnson, 2011; Welmerink, 2012). This finding raises the question of whether biologically compatible expansion is possible using specific combinations of fixed appliances and wires as claimed by some manufacturers. A recent study tested such claims by evaluating the effects of active (In-Ovation R; Dentsply GAC, Islandia, NY) and passive (Damon 3 MX; Ormco Corp, Orange, CA) self-ligating brackets on alveolar boundary conditions (Cattaneo *et al*., 2011). Buccal cortical bone thickness on the second premolars decreased significantly with both types of appliances, even though the change in buccolingual tip of the teeth was the same with both systems. Thus these findings do not support the claims that specific appliances generate biologically compatible forces in which the bone remodels to maintain its integrity despite substantial arch expansion during treatment. Similarly, it also is known that buccal crown tipping during RPE is accompanied by a concomitant decrease in both buccal bone thickness and buccal marginal bone height (Rungcharassaeng *et al*., 2007). Finally, slow palatal expansion using quadhelix or Schwarz appliances decreases and increases, respectively, buccal and lingual bone thicknesses (Tai *et al*., 2010a, 2010b; Corbridge *et al*., 2011).

Bimaxillary protrusion in which orthodontic treatment aims to reduce the dentoalveolar prominence is an example of a patient- plus treatment-specific variable that can contribute to compromised alveolar boundary resulting in dehiscences following incisor retraction (Sarikaya *et al*., 2002). Similarly, post-orthodontic increase in incisal proclination is known to be a risk factor for dehiscences (Fuhrmann, 1996). Such incisor proclination-related recession may be worse in patients with thin initial symphysis bone width (Wehrbein *et al*., 1996; Artun & Grobety, 2001). In general, it appears that both patient- and treatment-specific variables such as pre-treatment boundary conditions, the magnitude of expected dental movements, and the potential adaptability of the bone to remodel adequately with these movements may be important to the quality and quantity of bone retained following orthodontic treatment.

Quantifying CL/P defects and outcomes of alveolar bone grafts

Several studies have been performed using CBCT to determine its diagnostic efficacy in CL/P and to evaluate the success of alveolar bone grafts and paths of eruption of canines through grafted bone sites in these patients (Hamada *et al*., 2005; Oberoi *et al*., 2009, 2010; Quereshy *et al*., 2011; Garib *et al*., 2012; Zhang *et al*., 2012). In comparing CBCT with panoramic radiographs, it has been shown that while the panoramic radiograph enables the approximation of vertical bone height of the bone bridge, it does not permit determination of the buccal-palatal width of the bone, both of which can be discerned with CBCT (Hamada *et al*., 2005). Additionally, the CBCT images enable the visualization of the 3D morphology of the bone bridge, the relationship between the bone bridge and roots of neighboring teeth, and their periodontal condition. A subsequent study that compared patients before and after cleft grafting demonstrated an 84% bone fill of the cleft defect 1 year following the graft (Oberoi *et al*., 2009). This information is important in the decision process for implant placement. Additional studies have reported a large range for graft volume of between 6.1 mm^3 (Oberoi *et al*., 2009) and 489 mm^3 (Quereshy *et al*., 2011) at cleft sites for unilateral CL/P. Such determinations from CBCT are valuable in pre-surgical planning of graft site reconstruction and bone harvesting. In addition, studies on canine eruption following grafting demonstrate no significant differences in absolute incisal, facial, and mesial distances traveled between cleft-side and non-cleft-side canines. However, the movement of the cleft-side canines does not mimic that of the non-cleft-side canines and more of the cleft-side canines tend to be impacted. It remains to be determined whether the alveolar boundary conditions and bone quality of the bone graft contribute to these differences in canine eruption. These findings and their clinical implications are discussed in greater detail in Chapter 23.

Orthognathic surgery

CBCT continues to provide useful information for diagnosis, treatment planning and assessment of treatment outcomes for orthognathic surgery cases, which are discussed in greater detail in Chapters 20–22. These studies include the determination of changes in 3D hard and soft tissue facial anatomy (McCance *et al*., 1992; Soncul & Bamber, 2004; Honrado *et al*., 2006; Jung *et al*., 2009; Baik & Kim, 2010; Lim *et al*., 2010; Ryckman *et al*., 2010; Park *et al*., 2012; Kim *et al*., 2013), maxilla-mandibular relationships and positional changes in the condyle (Magalhaes *et al*., 1995; Lee & Park, 2002; Baek *et al*., 2006, 2009; Cevidanes *et al*., 2007; Mucedero *et al*., 2008; Draenert *et al*., 2010; Kim *et al*., 2010, 2011, 2012; Jakobsone *et al*., 2011), post-surgical relapse (Busby *et al*., 2002; Cevidanes *et al*., 2007; Proffit *et al*., 2007), and airway dimensions (Cevidanes *et al*., 2007; Chen *et al*., 2007; Degerliyurt *et al*., 2008; Carvalho Fde *et al*., 2010; Almeida *et al*., 2011; Hong *et al*., 2011; Motta *et al*., 2011). As discussed in Chapter 21, the changes resulting from orthognathic surgery can be determined in 3D by performing a superimposition of the pre- and post-treatment scans on the anterior cranial base, enabling depiction of the magnitude and direction of treatment changes via color maps or vectors (Cevidanes *et al*., 2005, 2010b).

The effects of surgery on airway patency also have begun to be elucidated and generally show that post-surgical changes in the cross-sectional area of the airway vary depending on the type of surgery and the site at which the airway is being assessed (see also Chapter 22). Thus, for example, mandibular setback surgery decreases the airway sagittal cross-section at the soft palate but not at the posterior nasal spine. In contrast, while both a single-jaw mandibular setback and two-jaw maxillary advancement/mandibular setback procedure are accompanied by narrowing of the airway, the two-jaw surgery tends to demonstrate comparatively fewer negative effects on the airway (Samman *et al*., 1992; Chen *et al*., 2007; Degerliyurt *et al*., 2008; Hong *et al*., 2011). These findings have implications for selecting optimal surgical approaches for OSA patients and are presented in greater detail in Chapter 22.

INCIDENTAL FINDINGS, DIAGNOSTICIAN SKILLS, AND MEDICO-LEGAL IMPLICATIONS

Identifying incidental findings and determining their frequency is important for insights into medico-legal implications and the capability of the diagnostician to interpret the images optimally. Incidental findings represent clinically relevant abnormal findings in radiographic images for which the image was not prescribed initially. The frequency of incidental findings varies between studies depending on the sample age, FOV studied, and methods for lesion characterization (Miles, 2005, 2009; Cha *et al*., 2007; Rogers *et al*., 2011). Given that CBCT has substantially more data than 2D radiographs and, therefore, captures more lesions both within and outside the dento-maxillofacial area, the rate of incidental findings is considerably higher in CBCT scans than in traditional radiographs. Indeed, whereas incidental findings are detected in approximately 3.5–8% of panoramic radiographs (Tetradis & Kantor, 1999; Kuhlberg & Norton, 2003; Bondemark *et al*., 2006; Asaumi *et al*., 2008), the frequency of detecting incidental findings in CBCTs is as high as 25–54% (Miles, 2005; Cha *et al*., 2007). The use of larger FOV images typically preferred by orthodontists as opposed to those favored by most other dental providers increases the likelihood of incidental findings in the imaged volume and its attendant consequences. Furthermore, the utilization of CBCT as a screening test with the expectation of discovering incidental findings when there are no relevant signs or symptoms or other appropriate justification for undertaking this type of imaging is not justified due to the risks of radiation (see also Chapter 6).

The most common incidental findings in CBCT include those associated with airways, the TMJ, endodontic lesions, developmental dental conditions, impacted teeth, soft tissue calcifications, and lesions of bone (Caglayan & Tozoglu, 2012; Price *et al*., 2012). Of the incidental findings reported by Price and colleagues (2012), 16.1% required intervention or referral, 15.6% required monitoring, while the remainder (68.3%) required no further treatment. This finding and others suggest that while most incidental lesions do not carry serious consequences for the patient, more serious unsuspected lesions, including those of the cranial base and cervical spine (Kau *et al*., 2005; Nair *et al*., 2007; Popat *et al*., 2008; Miles, 2009) that require follow-up or treatment, may be present in CBCTs (see also Chapter 10). Up to 60–86% of incidental findings have been reported to be in extragnathic sites (Cha *et al*., 2007; Abdul-Kader, 2008), which typically are less familiar to a radiologically untrained diagnostician (Ahmed *et al*., 2012). It also currently is not known what proportion of incidental findings in CBCT scans are relevant orthodontically and would lead to modifications in treatment approaches. Such knowledge would be critical in determining whether the prevalence of treatment-modifying findings is adequately high to justify the more universal use of CBCT in orthodontics.

It is important to recognize that the diagnostician, whether the radiology specialist or an appropriate healthcare provider who chooses to interpret a radiographic image, bears legal and ethical responsibilities for identifying all anomalies in the entire prescribed FOV that may potentially affect the patient's health and, when needed, for referring the patient for follow-up (Turpin, 2007; Friedland, 2009; Miles, 2009; AAO Insurance Company, 2010; see also Chapter 7). The current guidelines also state that all CBCT scans should be read in their entirety, with all regions covered by the scan being the responsibility of the diagnostician (Turpin, 2007). Because no laws exist yet as to who should read the CBCT scans, the diagnostician can be either the orthodontist or the radiologist. If an orthodontist elects to interpret the information from CBCT scans, he or she has accepted a greater duty to the patient than that to which he or she otherwise would be obligated (AAO Insurance Company, 2010). Because of these reasons and the higher propensity for incidental findings in CBCT scans than in 2D radiographs, it is important that diagnosticians have the necessary knowledge and ability to identify pathologies within the entire scan.

The above considerations lead to an important question, namely, "What is the capability of the orthodontist to identify non-orthodontically relevant findings and to make appropriate referrals when necessary?" Lack of recognition of incidental lesions can have substantial medico-legal ramifications (Zinman *et al*., 2010; see also Chapter 7), while the inadvertent diagnosis of false-positive findings by the untrained eye has the potential to add unnecessary healthcare costs due to secondary tests and treatments, as well as to contribute needless anxiety to the patient and family. In the study by Ahmed and associates (2012), orthodontists and orthodontic residents were found to miss approximately 67% of lesions and had a 50% false-positive detection rate in CBCT images. Following a 3-hour training by an oral and maxillofacial radiologist, the error rate in these two measures dropped to 43% and 35%, respectively. Although no data currently are available for error rates with CBCT or CT for oral and maxillofacial radiologists, historical norms of missed lesion error rates in medical radiology range from 4 to 13.5% (Renfrew *et al*., 1992; Wechsler *et al*., 1996; Berlin, 2005) versus about 43% post-training error rate for orthodontists obtained in this study. These studies show for the first time that orthodontists and orthodontic residents currently do not have the necessary background to read and interpret CBCT scans optimally and that an appropriately trained diagnostician such as an oral and maxillofacial radiologist should be consulted for the interpretation of CBCT scans, as recommended by others (Turpin, 2007; AAO Insurance Company, 2010). These findings also suggest that increased training of orthodontists in viewing normal and abnormal anatomy in CBCT images would provide additional valuable skills for them to further identify important components further relevant to orthodontic diagnosis and treatment planning.

INDICATIONS: EFFICACIOUS USE OF CBCT IN ORTHODONTIC DIAGNOSIS AND TREATMENT PLANNING

CBCT and 3D imaging in orthodontic diagnosis and treatment planning

Accurate imaging is an essential requirement in orthodontics for deriving an appropriate diagnosis, formulating an optimal treatment plan, and monitoring and documenting treatment progress and outcome. Until recently, the information needed to arrive at a diagnosis and treatment plan has relied on a combination of 2D data obtained from photographs and conventional radiographs and 3D visualization derived through clinical examination of the patient and analysis of plaster casts. Recent advances in digital technology have provided the means to evaluate study models, as well as facial, skeletal, and dental morphology and relationships using CBCT, in 3D.

Despite the increasing popularity of CBCT, there is a range of opinions among clinicians on the overall utility of CBCT in orthodontics. This spans from those who advocate for its routine use for all orthodontic patients to those who recommend its use in specific cases in which conventional radiography cannot supply satisfactory diagnostic information and where the CBCT-derived information may enhance diagnosis and/or lead to refinements or alterations in treatment plans (Isaacson *et al*., 2008; SEDENTEXCT, 2009, 2011). The latter approach to CBCT imaging has been endorsed by the American Association of Orthodontists (AAO), which adopted a resolution stating that while the organization recognizes that "there may be clinical situations where a cone beam computed tomography (CBCT) radiograph may be of value, the use of such technology is not *routinely* required for orthodontic radiography" (AAO, 2010). This implies that the justification for using CBCT in orthodontics is linked intricately to its diagnostic and therapeutic efficacies, for which research has been performed in a relatively small subset of clinical problems that include impacted teeth, CL/P, and orthognathic surgery. Thus, determining the efficacy of CBCT in enhancing orthodontic diagnosis and therapeutic decisions is a key area in need of substantial future research focus, not only to validate the utility of the technology in specific situations, but also to define clinical protocols that will generate optimal information with minimal radiation exposure, as discussed later.

Hierarchy of evidence in the use of CBCT

Although CBCT clearly enhances the visualization of normal and abnormal anatomy and pathologies, scientific evidence on the impact of the additional information obtained in refining or changing orthodontic treatment plans in several clinical situations remains to be determined. Nevertheless, with increasing clinical utilization and research studies, a hierarchy of indicators for CBCT imaging is emerging. Ideally, the utilization of any new technology should be supported by the highest level of evidence generated from rigorous scientific studies that demonstrate that its use enhances diagnosis in a significant number of cases when compared with currently available technology and, in the longer term, is shown to improve treatment results, efficacy, and efficiency (Figure 1.4; SEDENTEXCT, 2009, 2011; see also Chapter 6). In the absence of such proof, the next level of evidence that can be used to justify use of the technology is provided by published case reports showing its contribution to improved diagnosis, treatment plan or outcome, or any combination of these for a specific type of case, which could be applicable to other similar cases. If these two levels of evidence are not available, a clinician still may choose to utilize the technology if he or she believes that it likely would enhance the diagnosis and/or alter the treatment plan. Any one of these three tiers of evidence is important particularly in justifying the use of a technology such as CBCT, which has associated risks of radiation exposure and increased costs of imaging and interpretation as compared with the technologies it is intended to replace. When used for any of these three scenarios, it should be anticipated that the CBCT likely will provide information that could result in one or more of the following outcomes: (1) enhance diagnosis by localizing the site of aberration as for impacted and transposed teeth, (2) quantify the magnitude of defect or deformity as for CL/P,

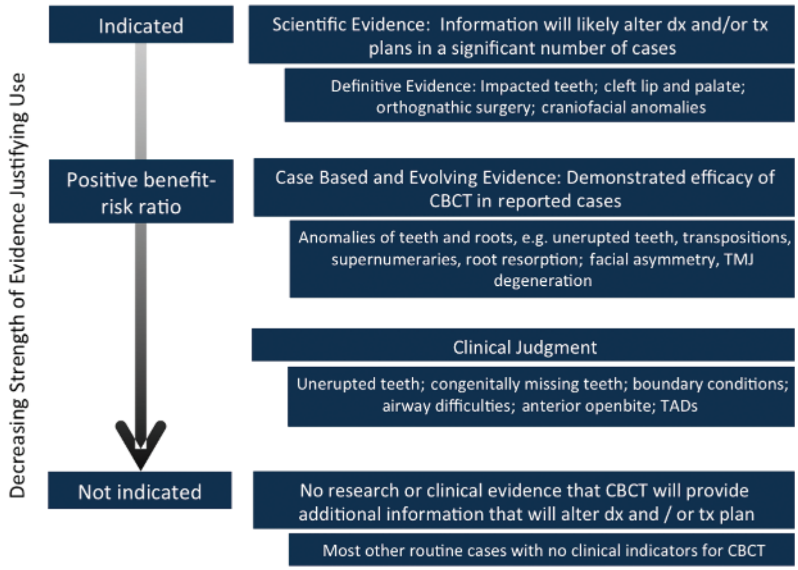


Figure 1.4 Clinical scenarios in which the use of CBCT may be indicated on the basis of research evidence or case- or clinical judgment–based determination of the need for imaging. All three levels of indicators require a careful consideration of the benefit-to-risk analyses prior to undertaking CBCT.

(3) help to provide a differential diagnosis on whether the defect is skeletal, dental, or both, (4) identify the jaw(s) involved and determine whether the aberration is bilateral or unilateral (e.g., as in orthognathic surgery, asymmetry, craniofacial anomaly, and openbite cases), and (5) help point to possible cause(s) of these findings such as for openbites or asymmetries resulting from TMJ degeneration. The expected benefit of the enhanced 3D information derived from CBCT relative to that obtained from traditional 2D radiographs ultimately may span from a refinement of treatment to a total modification in the treatment rendered.

Whether supported by research evidence or a potential positive benefit-to-risk outcome, the decision to undertake a CBCT examination should be made only after the clinician has carefully evaluated the patient history and chief complaint, performed a clinical examination, and, where indicated, taken traditional 2D radiographs (Figure 1.5). Such a careful selection of patients for CBCT imaging will ensure maximum benefit while avoiding unnecessary risks to patients who do not need this diagnostic imaging. Based on a synthesis of current scientific evidence, case reports, and other available information, the section below summarizes clinical scenarios where CBCT may be beneficial and ways to use this imaging modality under specific circumstances. The examples provided are by no means all-inclusive, and the proposed benefits of CBCT in some instances may be conjectural at this point. These and additional possible applications of CBCT in specific case types are discussed in greater detail in several chapters in Sections III and IV of this book.

Research evidence-based use of CBCT

Impacted and transposed teeth

Impacted and transposed teeth possibly are the most common indications for CBCT imaging in orthodontics. Of the many clinical situations presented to the orthodontist, impacted teeth are one in which CBCT has been shown to improve diagnosis and contribute to modifications in treatment planning in a significant number of subjects (Walker *et al*., 2005; Haney *et al*., 2010; Katheria *et al*., 2010; Botticelli *et al*., 2011; see also Chapter 16). CBCT

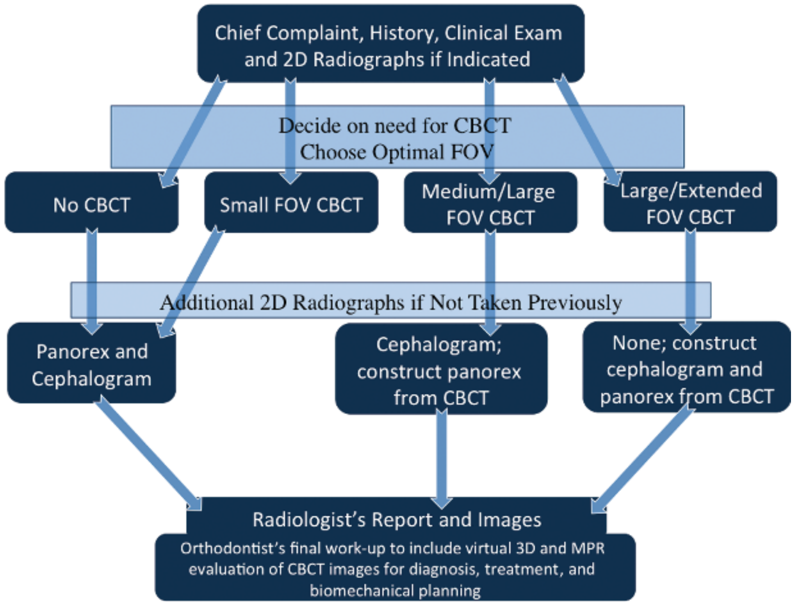


Figure 1.5 Decision tree for CBCT and 2D radiographic imaging of the orthodontic patient. Decisions on whether or not to take a CBCT and the choice of FOV should be made on the basis of a thorough knowledge of the chief complaint, history, clinical examination, and, if needed, 2D radiographs. The selection of any further 2D radiographs required should be based on the CBCT FOV and whether the patient has had any 2D radiographs taken during the initial work-up. The orthodontist then should utilize all the information collected, including that from the radiologist's report and virtual evaluation of the CBCT, to refine the diagnosis and derive an optimal treatment and biomechanical plan.

enhances the ability to localize impacted canines accurately, evaluate their proximity to other teeth, determine the follicle size and presence of pathology, estimate space conditions, and assess resorption of adjacent teeth (Walker *et al.*, 2005; Haney *et al.*, 2010; Botticelli *et al.*, 2011; Alqerban *et al.*, 2011b; Figure 1.6 and Figure 1.7). Additionally, CBCT imaging not only aids in tooth localization and choice of site for surgical access for a significant number impacted teeth, but also contributes to a significantly higher confidence in diagnosis and treatment planning relative to the combination of panoramic, periapical, and occlusal radiographs that traditionally have been used for this purpose (Haney *et al.*, 2010). More important, the findings also demonstrate that the original treatment plans derived from 2D radiographs are changed for more than 25% of the impacted teeth when orthodontists viewed these teeth in CBCT images. These findings are in concordance with those reported by others (Katheria *et al.*, 2010; Botticelli *et al.*, 2011). The scientific evidence for the utility of CBCT in both refining diagnosis and modifying treatment plans for significant numbers of impacted teeth validates its use for impacted teeth. Some of this scientific evidence on the superiority of CBCT to 2D radiography could be applicable to supernumerary and transposed teeth.

From a clinical standpoint, besides providing detailed information on impacted and transposed tooth location and associated root resorption and pathologies, CBCT facilitates the accurate definition of the relationship of these teeth to neighboring structures and teeth, assists in planning surgical access and bond placement, and helps in defining the optimal direction for extrusion into the oral cavity. The latter information is useful for two reasons. First, it can help minimize or prevent damage to adjacent tooth roots by defining a safe tractional path or, where this is not possible, it can help in the determination of proactive movement of any interfering tooth and root out of the

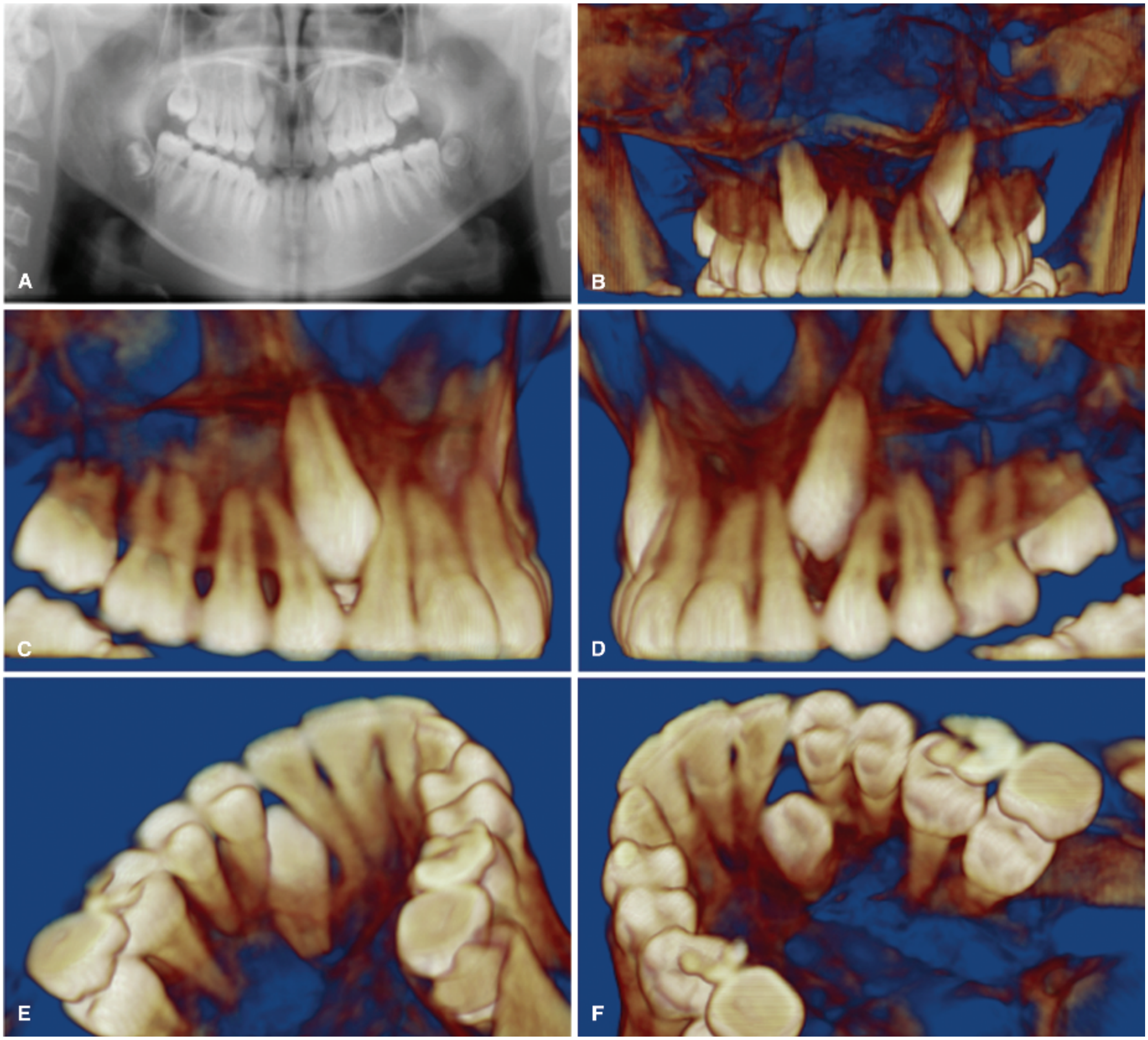


Figure 1.6 Depiction of impacted maxillary canines using a conventional 2D panorex (*A*) and 3D volumetric renderings (*B–F*). The 3D images permit clear visualization of the location and relationships of the impacted canines to adjacent structures, as well as the presence of any root resorption. The detailed information obtained facilitates treatment decisions, including determination of teeth to be extracted in extraction cases such as the one in this figure, optimal surgical approach, appropriate placement of attachments, and biomechanics planning.

tractional path so as to avoid damage. Second, the determination of the direction and path(s) for traction from CBCT aids in designing the appliance or spring optimally to move the tooth most efficiently into the dental arch and occlusion (see also Chapter 16). Increased accuracy of tooth size measurement with CBCT compared with 2D radiographs can aid in determining and developing proactively the space needed to fit the tooth into the arch. Overall, it can be expected that the optimal and accurate utilization of information derived from CBCT to customize treatment for impacted and transposed teeth should result in increased efficiency and enhanced success rates for tooth retrieval.

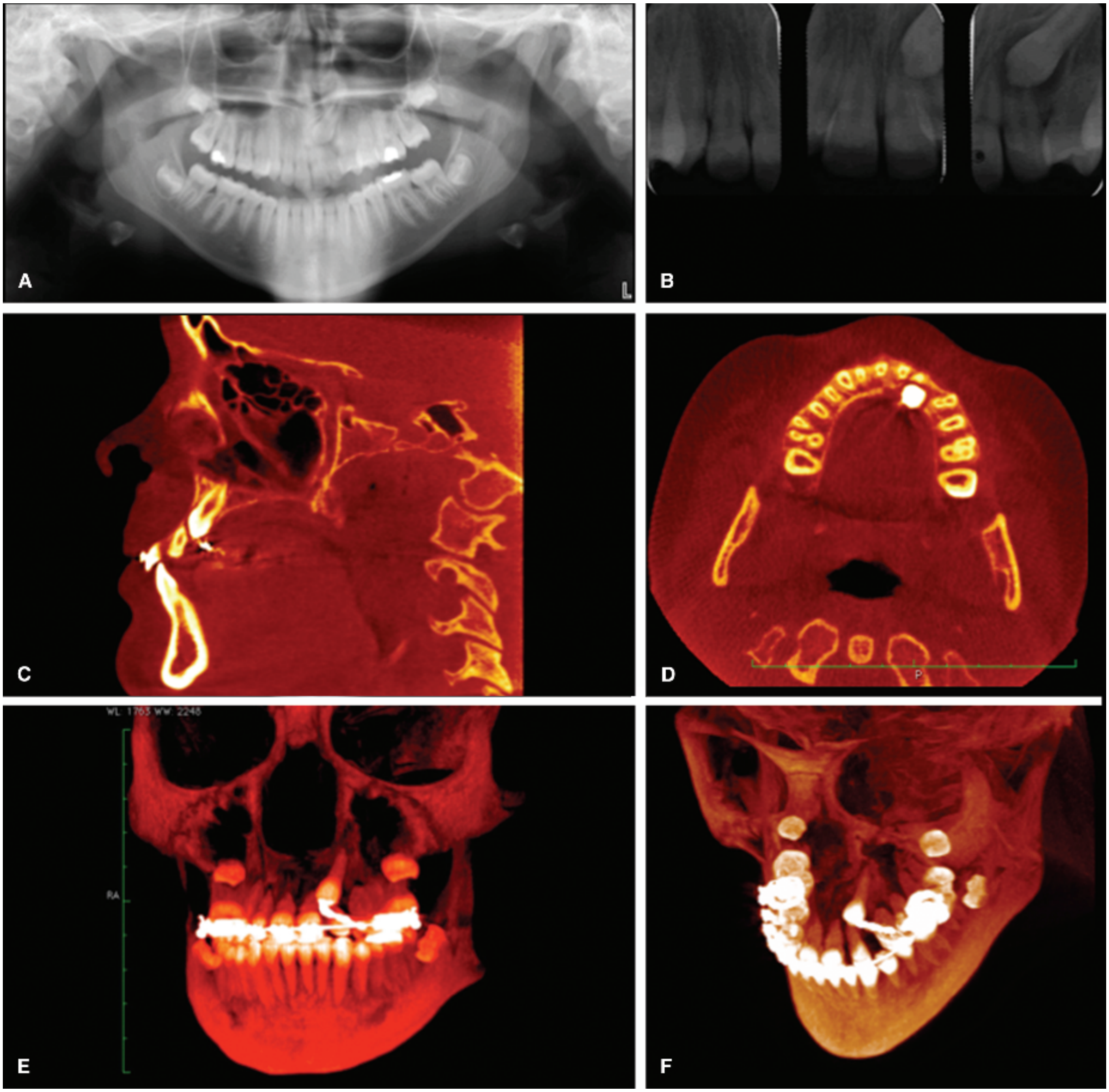


Figure 1.7 Utility of CBCT in diagnosis of localization of impacted teeth and identification of associated root resorption. 2D images are prone to superimposition and other limitations for this purpose that can be overcome with use of 3D radiography that can be useful in identifying precise location of the impacted tooth, its relationship with other structures, and any associated root resorption. In this case, pre-treatment panoramic (*A*) and periapical (*B*) radiographs are not adequate for precise location of the impacted tooth or discerning if root resorption truly is present. Approximately a year into treatment during which time the tooth failed to erupt, a CBCT scan was taken to reveal lateral and central incisor root resorption, as seen here in sagittal (*C*) and axial (*D*) sections and 3D volumetric renderings (*E* and *F*).

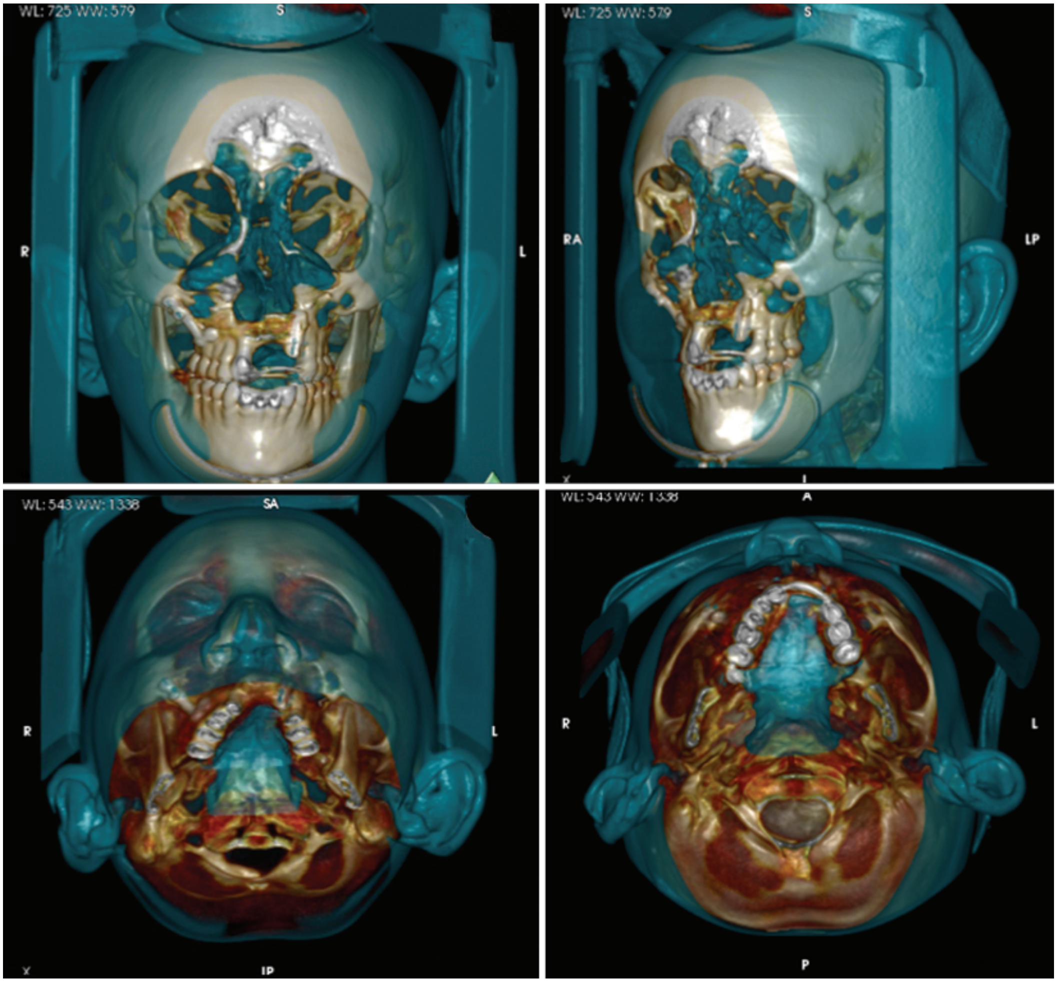


Figure 1.8 3D volumetric reconstructions of a patient with bilateral CL/P are useful in obtaining detailed information on the magnitude of the defect and the status and position of teeth at the defect site. This information can be valuable for diagnosis and treatment planning.

Cleft lip and palate (CL/P)

3D information has been shown to be valuable in determining the volume of the alveolar defect and, therefore, the amount of bone needed for grafting in CL/P patients and for determining the success of bone fill following surgery (Oberoi *et al*., 2009; Shirota *et al*., 2010; Figure 1.8). Other valuable information obtained from CBCT in CL/P patients includes the numbers, quality, and location of teeth in proximity to the cleft site (Zhou *et al*., 2013), the eruption status and path of canines in grafted cleft sites (Oberoi *et al*., 2010), and diagnosing for implant placement (see also Chapter 23).

Orthognathic and craniofacial anomalies surgical planning and implementation

CBCT combined with computer-aided surgical simulation (CASS) or computer-aided orthognathic surgery (CAOS) offers many novel enhancements including refining diagnosis and optimizing treatment objectives in 3D and virtual treatment

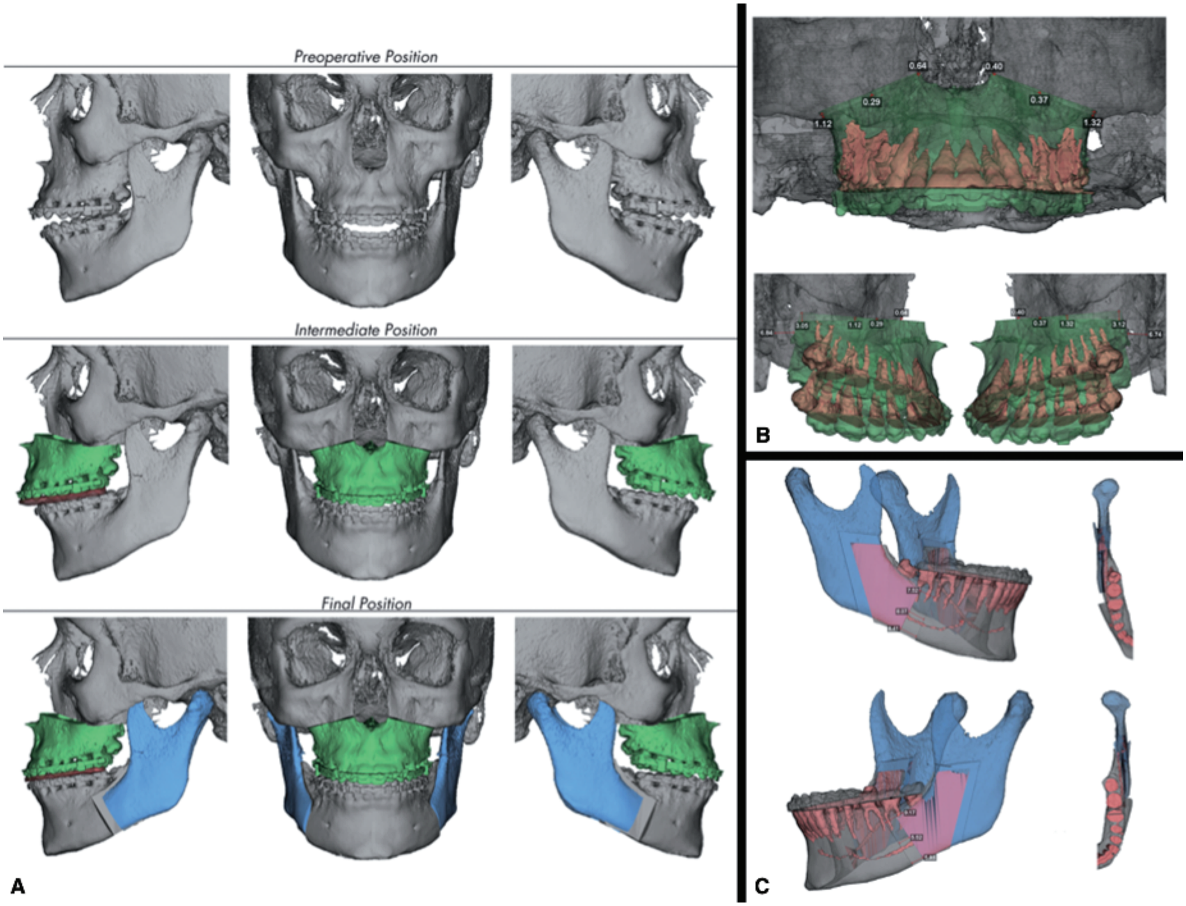


Figure 1.9 Virtual surgical treatment planning for a patient to visualize and determine the magnitude of maxillary and mandibular movements, as well as any complication such as proximal segment interferences that may arise during surgery. The patient's treatment objectives include maxillary impaction to address the openbite and bimaxillary advancement to mitigate obstructive sleep apnea. *A*: An intermediate step involving maxillary advancement and impaction is planned followed by determination of the corresponding mandibular advancement. *B*: Depiction of the magnitude of maxillary movements. *C*: Depiction of mandibular movements and potential proximal segment interferences. The virtual treatment plan then is used to generate an intermediate occlusal wafer and a surgical splint using stereolithography (SLA) or selective laser sintering (SLS).

planning to improve surgical procedures and outcomes (Xia *et al*., 2000a, 2000b; Hassfeld & Muhling, 2001; Troulis *et al*., 2002; Gateno *et al*., 2003, 2007; see also Chapters 20–22). In particular, virtual surgical procedures facilitate the planning of osteotomies, minimizing damage to structures such as nerves, visualizing and planning for interferences such as those of proximal segments, and fabrication of customized fixation devices for orthognathic surgery (Figure 1.9). CBCT with or without co-registered 3D images from other sources such as those from dental casts also can be used to construct physical anatomic models that typically are fabricated in a 1:1 ratio by 3D printing such as stereolithography (SLA) or selective laser sintering (SLS). These physical models can be used to simulate or test treatment options and construct anatomically correct replacement grafts, although they now are used less commonly for this purpose than virtual models. The importance of these approaches as a tool during surgical procedures has been validated by several investigations showing that computer-aided surgery facilitates the prediction of potential surgical complications, decreases the length of surgery, and results in outcomes similar to or better than those of traditional approaches (Xia *et al*., 2000a, 2000b; Hassfeld & Muhling, 2001; Troulis *et al*., 2002; Gateno *et al*., 2003, 2007). Thus, CBCT should be considered an important diagnostic and treatment planning adjunct for cases that will be treated with orthognathic or craniofacial surgery.

3D CBCT imaging is useful particularly in the diagnosis and treatment planning of asymmetries, where discrepancies often manifest in all three planes of space. Facial asymmetries may involve perturbations in the size and shape of the maxilla and/or the mandible in which any number of anatomic structures, including the condyle, condylar neck, ramus, and body of the mandible can be affected. Combined asymmetry in pitch, roll, and yaw produce deformities in the skeletal bases and dental arches. The differences in the bilateral anatomy determined through CBCT facilitates a refined and quantifiable diagnosis of asymmetries that, if clinically significant, may alter a given treatment plan in both growing individuals and adults. When large differences exist between bilateral structures, CBCT scans enable the use of a technique called “mirroring,” in which the normal side is mirrored onto the discrepant side so as to simulate and visualize the desired end result, as well as to plan the surgery to facilitate correction (Metzger *et al*., 2007; see also Chapter 21). Other surgical cases in which 3D CBCT imaging is likely to offer advantages over 2D radiography in diagnosis and treatment planning include those with CL/P (as discussed earlier) and craniofacial anomalies such as hemifacial microsomia, cleidocranial dysplasia, and ectodermal dysplasia.

Case-based and clinical judgment-based use of CBCT

Other than the above clinical entities, the utility of CBCT in other orthodontic situations has been demonstrated through case reports or may be justified based on the provider’s clinical judgment of a positive benefit-to-risk analysis. These clinical scenarios encompass anomalies of teeth and roots, including supernumerary teeth, transpositions, and root resorption; TMJ degeneration; suspect boundary conditions; airway concerns; and the determination of possible contributors to or causes of open bites.

Supernumerary teeth

The presence of supernumerary teeth can pose a challenge in the ability to distinguish which tooth is actually the “supernumerary” and which is the “normal tooth” (Katheria *et al*., 2010). Accurate measurements and the determination of the precise location of the tooth from CBCT images may allow the clinician to make an informed decision on which tooth or teeth to extract on the basis of size, shape, and retrievability of the teeth; the most optimal surgical approach; as well as help to minimize damage to the normal tooth. These points are illustrated well in a case (Figure 1.10) showing the advantages of CBCT over routine radiography in deriving optimal diagnostic information and refined treatment approaches.

Root resorption

For generalized root resorption or that associated with impacted teeth, CBCT scans provide more sensitive and accurate information than do periapical or panoramic radiographs (Alqerban *et al*., 2009b, 2011b; Durack *et al*., 2011; Ponder *et al*., 2012; Ren *et al*., 2012; see also Chapter 15; Figure 1.7). Thus, detection of mild to moderate pretreatment root resorption by CBCT that may go undetected by 2D radiographs could lead to modifications in treatment plans, such as avoiding extractions in borderline cases to reduce the duration of treatment and magnitude of tooth movement to mitigate additional root resorption. However, there currently is no information that there are differences in the detection of substantial EARR between 2D and CBCT radiography or that its discovery by CBCT during treatment would lead to a treatment decision different from that made if the resorption was detected in 2D radiographs, which typically would entail stopping the treatment at least temporarily. In contrast, it is

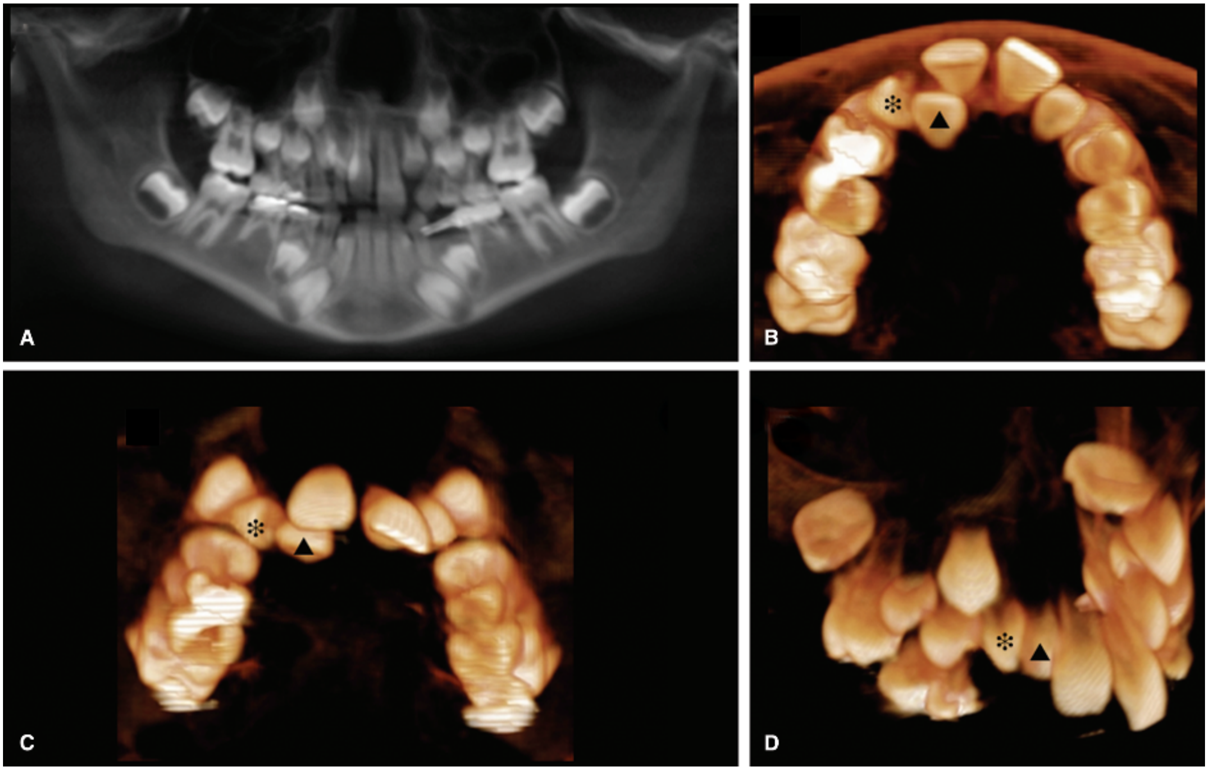


Figure 1.10 CBCT images offer important information and finer details in treatment planning of supernumerary teeth. *A*: A panoramic view extracted from the CBCT scan shows the presence of a supernumary tooth in the upper right lateral incisor area with delayed eruption of the maxillary right central incisor. It is difficult to discern from the panoramic view (or even from periapical radiographs, not shown) which of the two teeth, marked * and ▲ would be optimal morphologically to serve as the lateral incisor. Since the contralateral lateral incisor has not erupted yet, it cannot be examined clinically for size and form for comparison. *B–D*: Various 3D views from CBCT scans allow the comparison of the two teeth on the right lateral incisor area with the unerupted left lateral incisor. An analysis of the mesiodistal measurements of these unerupted teeth revealed that the tooth marked * most closely matches the contralateral lateral incisor morphologically and dimensionally, with tooth marked ▲ being almost 1 mm larger mesiodistally than the contralateral lateral incisor. (Reprinted with permission from Kapila *et al*., 2011.)

plausible that detection of buccal or lingual root resorption by CBCT that is not visualized by 2D radiographs could differentiate pre- or in-treatment decisions made with the two imaging modalities. The question that remains to be answered in this scenario is how and when a clinician would decide that a patient has undergone such buccal and/or lingual root resorption to justify taking CBCT scan. Because of these considerations, additional work remains to be performed to validate the diagnostic utility and protocols for the use of CBCT for generalized root resorption.

For root resorption associated with impacted teeth, CBCT scans provide substantially superior visualization of roots than routine radiographs by eliminating artifacts resulting from superimposition of structures and depicting the 3D root structure from all possible directions (Alqerban *et al*., 2009b, 2011b; Figure 1.7). This enhanced information derived from CBCT scans relative to that from

2D images may be critical in changing treatment plans, including the option to extract a resorbed lateral incisor rather than a premolar in an extraction case. Although such treatment decisions appear to be a logical clinical outcome with the use of CBCT, the effects of the superior information derived from CBCT images in modifying treatment decisions as well as determining the threshold of root resorption at which a clinician opts to extract a tooth with a resorbed root rather than a healthy premolar remain to be seen. Finally, the detection by CBCT of abnormal anatomy of the root, such as dilacerated roots—particularly in the bucco-lingual direction not seen in 2D radiographs—also may help determine the amount and direction that a dilacerated tooth can be moved or may aid in the decision to extract it.

Miscellaneous dental anomalies

Other dental anomalies that may benefit from CBCT imaging over traditional radiographs include delayed or unerupted teeth and congenitally missing teeth.

Alveolar boundary conditions

CBCT imaging can help verify alveolar boundary conditions that typically are not observable by 2D radiographs that either may be inadequate prior to treatment or may become compromised during tooth movement. Compromised or limited pretreatment alveolar boundary conditions may limit or interfere with the planned or potential tooth movement, as well as the final desired spatial position and angulation of the teeth. Failure to diagnose compromised alveolar bone prior to treatment and to factor this into the treatment plan likely will lead to worsening of the problem during orthodontic treatment. The visualization and characterization of boundary conditions is performed best by carefully analyzing MPR and volumetric CBCT information during the initial workup (Figure 1.11), which may aid in implementing alternative treatment strategies when indicated.

As with other types of cases, it is best to be selective about which cases may benefit from CBCT scans for assessing alveolar boundary conditions. These include those presenting with alveolar bone phenotypes that clinically appear too narrow to accommodate significant labio- or bucco-lingual displacements or changes in angulations of teeth (Figure 1.11), those with compromised periodontium and/or gingival anatomy, those where the planned orthodontic movements are substantial enough such that the bone anatomy is not likely to adapt to these movements, and those where the movement of the tooth may entail translocating it past another tooth or obstruction (Figure 14.3). As discussed in Chapter 14, specific clinical situations that may pose challenges related to boundary conditions include those with existing thin or compromised labial and/or buccal anatomy of the alveolar bone, transposed or ectopic teeth, bimaxillary protrusion involving an extraction treatment plan, camouflage treatment of compensated dentoalveolar structures where round-trip orthodontic mechanics is used, dilacerated roots, and where bone is deficient or missing (i.e., CL/P). Precise information on alveolar boundary conditions also may be helpful in treatment planning decisions for situations that require moving teeth close to the alveolar boundaries such as in borderline nonextraction cases or in situations where teeth are being decompensated, such as commonly is performed in orthognathic surgery cases. CBCT-aided diagnosis of fenestrations may be useful in planning treatment to torque roots back into bone using sophisticated biomechanics combined with TADs.

TMJ degeneration, progressive bite changes, functional shifts, and responses to therapy

A radiographic examination of the TMJ is an important component in the diagnosis and monitoring of responses to therapy in TMJ diseases in which the articulating osseous tissues or joint spatial relationships are compromised (Okeson, 1996). However, conventional 2D radiography of the TMJ including panoramic radiographs and cephalograms do not provide an accurate characterization of the joint because of distorted images with superimposed structures. Although TMJ tomograms are superior to other 2D radiographs of the TMJ, they provide only information limited to a few sections of the joint. In contrast, CBCT images the entire joint with visualization of minor to overt osseous hard tissue morphologic changes

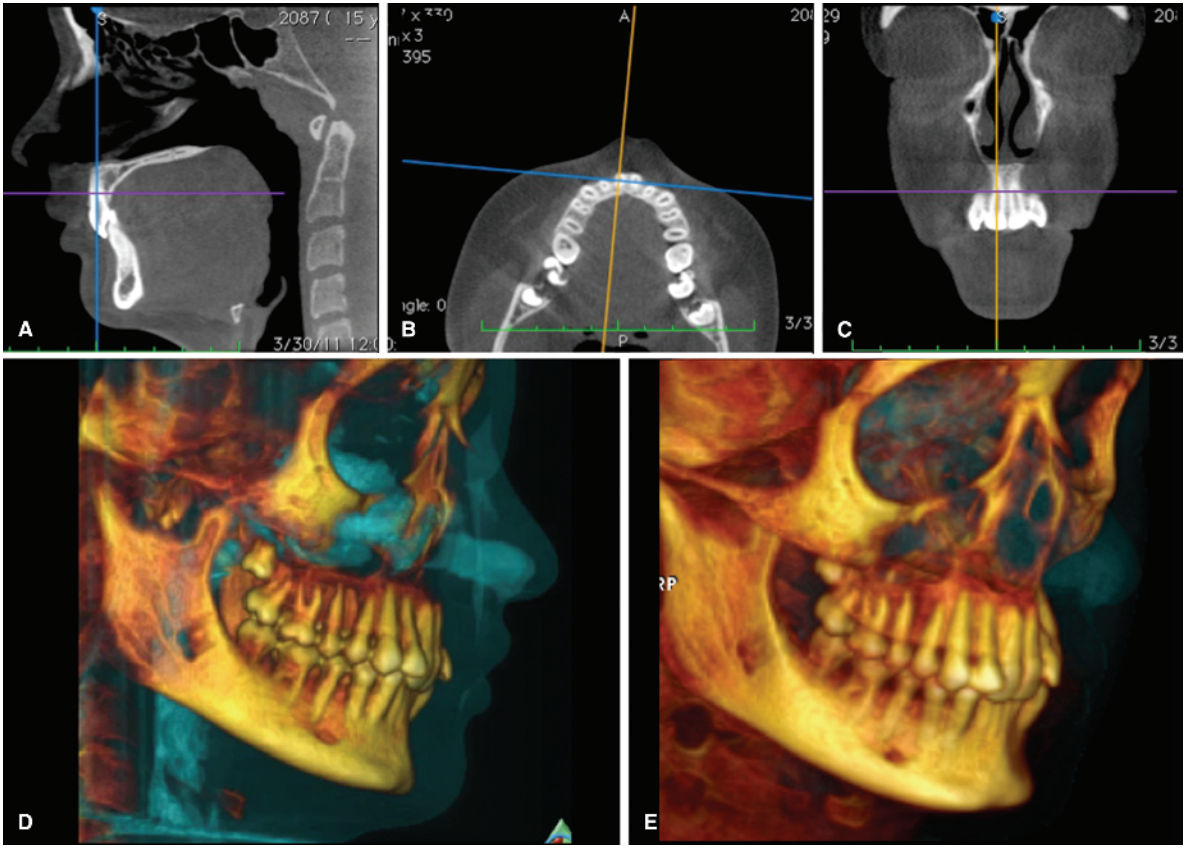


Figure 1.11 Determination of anterior boundary conditions in a case with severely retroclined maxillary and mandibular incisors using sagittal (*A*), axial (*B*) and coronal (*C*) multiplanar, and 3D volumetric (*D* and *E*) reconstructions. This patient with a severe Class II division 2 malocclusion presents with upper incisor roots that have limited buccal bone support that could be placed into a better relationship with the bone through lingual root torque. In contrast, the lower incisors are retroclined severely and the boundary conditions may not adapt adequately during orthodontic flaring of these teeth. Information such as this could be helpful in planning treatment and defining the optimal methods to move teeth.

and congruency of bone surfaces that define the joint space resulting from pathology and adaptive processes and allows for accurate detection and evaluation of pathological changes (Honda *et al*., 2006; Honey *et al*., 2007; Figure 1.12). Radiographic signs of bony changes associated with TMJ arthritides include irregular and possibly thickened cortical outlines (sclerosis), erosions, osteophyte formation, subchondral cysts, and flattening and narrowing of the joint space (Gynther *et al*., 1996; Ahmad *et al*., 2009; Alexiou *et al*., 2009). Since these changes occur in a spectrum of TMJ diseases including OA, rheumatoid arthritis (RA), idiopathic condylar resorption, and other less common diseases, CBCT alone without history and clinical findings cannot distinguish between these disorders but can be useful for refining their diagnosis or responses to therapies. For example, early diagnosis and treatment of destructive inflammatory conditions, if determined clinically and/or by imaging, could prove advantageous since it has been shown that early intervention is important for controlling further bone destruction successfully (Allaart *et al*., 2006), which, in turn, can be monitored by CBCT (Finzel *et al*., 2011).

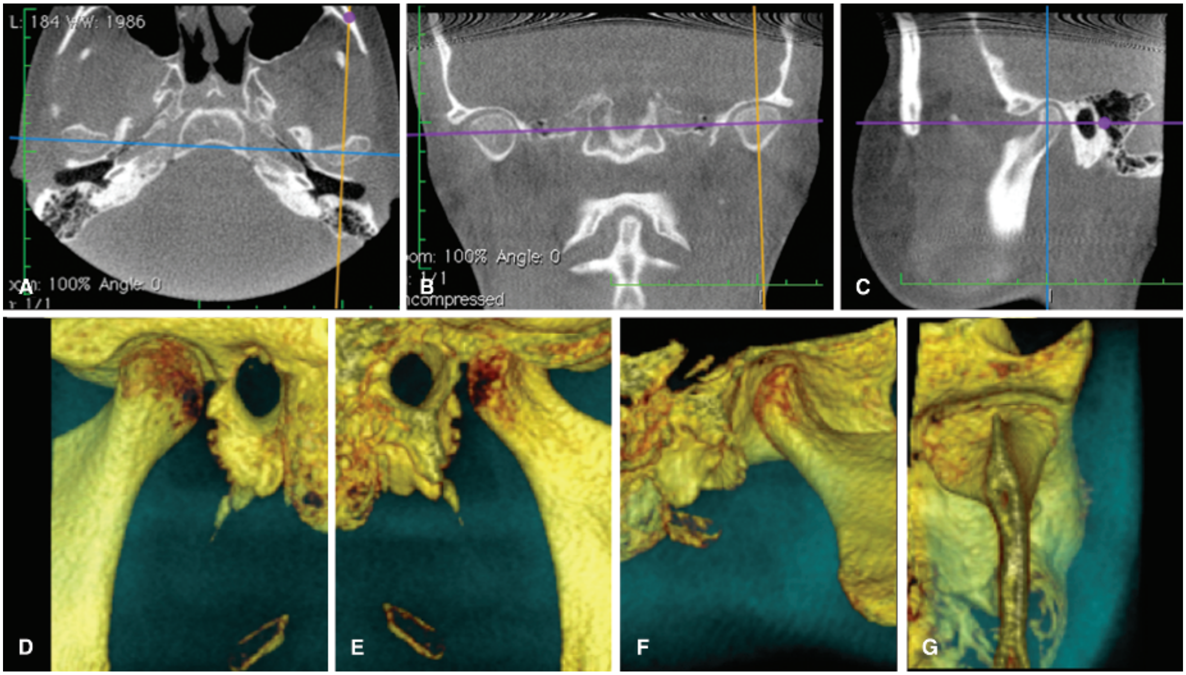


Figure 1.12 Visualization of the TMJ in the axial (*A*), coronal (*B*), and sagittal (*C*) planes, as well as 3D volumetric reconstructions here visualized from the buccal (*D*), medial (*E*), medio-inferior (*F*), and antero-inferior (*G*). Such detailed visualization without any superimposition of structures and in 3D can help in the identification of pathologic changes, including sclerosis, flattening, erosions, osteophytes, abnormalities in joint spaces, and responses of the joint tissues to therapy. Although these changes are visualized more clearly by CBCT than 2D radiography, there is little current evidence that the findings lead to changes in treatment plans.

While relatively infrequent, some patients who have TMJ pathologies such as temporomandibular joint disorders (TMJDs) or developmental disorders, including condylar hyperplasia, hypoplasia, or aplasia, undergo adverse morphologic and functional changes that include progressive bite changes, dental and skeletal compensations, and limitation or deviation of jaw movements (Helenius *et al.*, 2005; Koyama *et al.*, 2007; Alexiou *et al.*, 2009; Yura *et al.*, 2010) that contribute to unpredictable orthodontic outcomes. When these conditions occur during development, they can result in perturbed growth of the condyle on the affected joint, a decrease in ipsilateral mandibular growth, and accompanying compensations in the maxilla, tooth position, occlusion, and cranial base (Guyuron, 1988). Bilateral degenerative changes in the TMJ also may alter the facial growth pattern, resulting in adverse skeletal and dental changes in the vertical, horizontal, and transverse directions and contributing to mandibular retrusion, anterior open bite, and Class II malocclusion (Yura *et al.*, 2010). Because of the large numbers of structures involved and the inherent limitations of 2D radiography, changes resulting from these disorders are difficult to characterize accurately with conventional 2D radiography. In contrast, by allowing the concurrent visualization of the TMJs and assessment of the maxillo-mandibular-spatial relationships and occlusion, CBCT images provide the opportunity to visualize and quantify the local and regional effects associated with the TMJ abnormalities. With further advances in the field, CBCT may provide the ability to monitor the effects of therapy on condylar morphology and repair and aid in assessing both the efficacy and potential prognosis of the treatment (see also Chapter 12). Although not yet studied or validated, CBCT may also offer some advantages in diagnosing the initial skeletal and dental relationships in patients with large centric relation/centric occlusion (CR/CO) shifts such that images taken in CR would provide a frame of reference of the pre-treatment findings in three planes to aid in treatment decisions.

Temporary anchorage devices (TADs)

While there is not a high level of indication for CBCT scans in the placement of TADs, these images can prove helpful for macro-anatomical analyses through visualization of neighboring structures such as tooth roots, sinuses, and nerves that can be valuable for avoiding damage or complications (see also Chapter 18), as well as for micro-anatomical evaluation of the quantity and quality of cortical bone that may determine primary and secondary TAD stability. These determinations can aid in identifying optimal sites for TAD placement, thereby enhancing the chances of success. For example, it has been shown that a location 4 mm palatal to the incisive foramen provides excellent bone volume for palatal bone screws (King *et al*., 2007; Gracco *et al*., 2008). A technique involving a high-resolution 0.1 mm slice thickness CBCT and rapid prototyping to fabricate surgical guides also has been described for placing TADs on the buccal aspect of the jaws. Although the use of CBCT for TAD placement may not be justified in routine cases and locations at this point, it could have applications where a TAD needs to be placed in sites with complex anatomical structures or relationships (Jung *et al*., 2012). In such situations, unless the CBCT is needed for other reasons as well, a limited FOV CBCT scan typically may be adequate.

Case types not indicated for CBCT utilization

Cases in which clinical examination with or without 2D radiographs indicates that CBCT will not provide valuable new information typically do not justify the utilization of CBCT. Although CBCT is used to a limited extent for constructing custom fixed appliances and/or fabricating custom wires, the utilization of CBCT for this purpose also remains questionable. This is because other non-radiologic digital imaging technologies are available that serve as adequate alternatives and the radiation exposure with CBCT makes the benefit-to-risk ratio for the utilization of this technology for this purpose extremely low. Even though CBCT provides information on roots that would not be available with other scanning modalities, no data presently are available to suggest that this enhanced information results in better or more efficient treatments. Finally, CBCT images taken primarily to enhance patient and parent education are not a justified use of this technology.

PROTOCOLS FOR UTILIZING AND INTERPRETING CBCT IN ORTHODONTICS

Imaging goals and protocols

CBCT imaging goals in orthodontics should include evaluation and, where indicated, measurement of anatomic features, size, and relationships. Anatomic features include orthodontic landmarks and anatomic descriptors that help to differentiate between normal and abnormal anatomy. An imaging protocol for orthodontic purposes should take several factors into consideration. First, the image should incorporate the desired FOV that, in turn, is determined by the ROI. The provider first must decide what the CBCT image needs to accomplish for a specific patient. This determination is made on the basis of a thorough clinical exam supplemented by 2D radiography when necessary (Figure 1.5). Depending on the needs of the patient determined by this evaluation, the orthodontist may prescribe a small, medium, large, or extended FOV. The small FOV is used for assessing individual teeth (impacted teeth, root morphology, supernumeraries), quadrants, or sites for TAD placement (Figure 1.13). The medium or large FOV includes the mandible, the maxilla, or parts of both and typically would be used when requiring information on occlusal relationships, localized asymmetries, or bilateral TMJ evaluations or when the condition(s) of interest (i.e., potentially adverse boundary conditions) are present in both arches or jaws. The large or extended FOV includes the

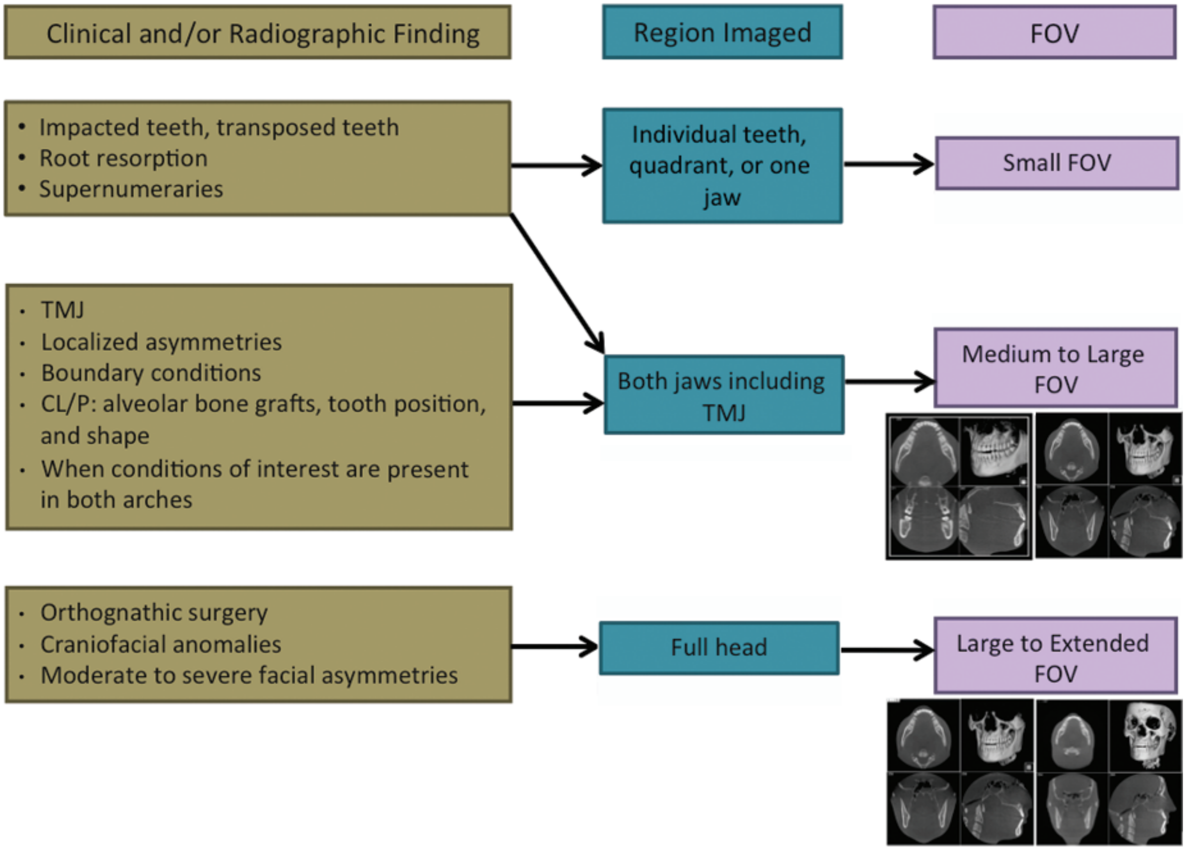


Figure 1.13 Protocol for the selection of appropriate CBCT FOV to obtain additional information following the discovery of specific findings from history and clinical examination. The choice of the FOV is based on the diagnostic objectives for the imaging as determined through a careful clinical assessment of the patient. The recommended FOV for specific needs also is dependent on the size of the individual. Thus, if the image of the entire craniofacial region is needed, it might entail using a large FOV for a child and an extended FOV for an adult. The FOV should default to the larger FOV indicated in each category when findings at distinct sites are being investigated so as to incorporate these ROIs in the FOV.

whole head and helps to visualize relationships between skeletal bases and between teeth and skeletal bases, as well as significant anomalies in patients requiring orthognathic surgery or having craniofacial anomalies. Obviously, the FOV also will be determined by the physical size of the subject; thus, a large FOV that primarily captures the maxilla and mandible of a large adult may be adequate to image the whole head of a child. It also is important to keep in mind that a smaller FOV not only decreases the radiation exposure to the patient but also has the added benefit of increasing the image quality, since the flat panel detector picks up less scattered radiation.

As discussed earlier, the initial interpretation of a CBCT scan should be performed by a diagnostician who has the necessary expertise for this purpose (Figure 1.14). Given the current status of the orthodontist's skills in interpreting CBCTs (Ahmed *et al.*, 2012), the scans ideally should be read by a radiologist. Once the CBCT report including relevant images is derived and communicated by the diagnostician, the orthodontist should extract additional details on the clinical entity

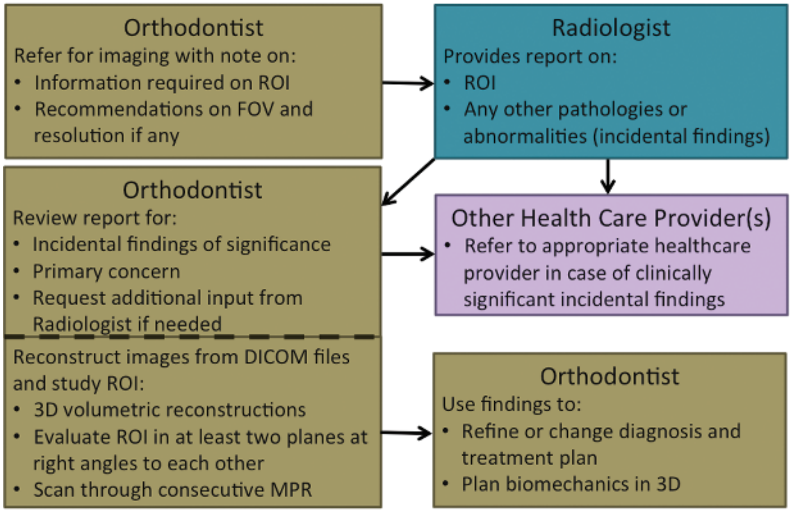


Figure 1.14 Protocol on image prescription and CBCT information extraction and management followed by appropriate patient referral and derivation of diagnostic information.

being imaged and any clinically relevant incidental findings from a review of the report and images provided. When clinically significant incidental findings are observed, the orthodontist and/or the radiologist should refer the patient to the appropriate healthcare provider. The orthodontist also should examine the entire volume virtually, particularly the ROI, to maximize the retrieval of clinically relevant information that may not be obvious in the radiologist's report. Therefore, it is important for the orthodontist to learn to use and manipulate 3D imaging software. Toward this goal, several user-friendly software programs now are available commercially and are relatively easy to utilize and master.

Following appropriate orientation of the images on the computer, the orthodontist should view the entire ROI from at least two planes at right angles to each other that will offer a multidimensional perspective, as well as the volumetric rendering in a 3D format (Figure 1.2; see also Chapters 2 and 8). In all, this protocol will enable the clinician to view an entire scan through 2D images in the axial, coronal, and sagittal planes, in addition to a 3D-rendered view, which can be rotated 360° or translated in three planes of space, offering up to six degrees of freedom. The information thus obtained should be used to refine diagnosis, modify the treatment plan, and optimize the biomechanics when indicated.

AREAS REQUIRING FURTHER STUDY

Despite promising studies and anecdotal support for the use of CBCT scans for specific clinical applications, the ultimate question to be answered is what true measurable quantitative and/or qualitative impact the observations from the scans have in modifying or enhancing diagnosis and altering or refining treatment plans. It is likely that future studies not only will address these questions, but also will help in modifying imaging protocols and image outputs, and possibly changing the overall strategies in which we approach the treatment of specific types of cases. For example, while CBCT scans are proving to be valuable in localizing impacted teeth, it is expected that the information gained increasingly will dictate the biomechanics by which we tract teeth, the direction of traction through the shortest possible path while minimizing damage to adjacent teeth, the optimal proactive placement of roots of neighboring teeth so that they are not damaged, and optimization of the placement of the tooth as it appears in the oral cavity (see also Chapter 16). Several additional examples are outlined later that offer rich opportunities for inquiry that may help better to define, delineate, and justify the utilization of CBCT in specific types of cases.

CBCT imaging is beginning to provide critical information on bone boundary conditions that previously was not available. Current orthodontic treatment entails moving teeth as best as possible within the constraints of the bone encasing the roots. Often, little consideration is given to the limits that the bone is capable of adapting around the roots and many clinicians practice mechanics in which teeth often are subjected to round-tripping. Thus, for example, in crowded cases treated with extraction therapy and continuous archwires, it is likely that the incisors will be flared before being retracted to their final position following space consolidation. It is not known yet if this compromises the quantity or quality of bone support, leads to increased incidence of fenestrations, or perhaps even increases root resorption. Such negative consequences could apply to other types of round-tripping tooth movements or to expansion beyond the permissible boundary conditions in all three planes. Further complicating the potential for these adverse responses are the possible effects that the pre-treatment bone biotype and alveolar anatomy may have on the likelihood for orthodontically mediated tissue damage. If supported by future research evidence, information from CBCT increasingly may become important in identifying patients whose bone anatomy and biotype will not be able to accommodate dental expansion to manage crowded arches, thus aiding in treatment decisions (see also Chapter 14). Such studies then could help provide guidelines that could be added to our diagnostic armamentarium when planning orthodontic treatments and also aid in identifying patients whose diagnosis and treatment would need to be modified on the basis of this CBCT data. As further scientific information on the limitations imposed by alveolar boundary conditions on orthodontic treatment become available, prior to commencing treatment the clinicians may be able to address additional questions such as: (1) Can the desired tooth movement be accomplished within the existing boundary conditions? (2) Will the boundary conditions be affected positively or negatively by skeletal or dento-alveolar expansion or tooth retraction? (3) What are the effects of compromised bone as in periodontal disease on the ability to move teeth in the sagittal or transverse planes? (4) What are the limits of bone adaptability and how is this affected by age, periodontal health, and the pre-treatment bone and anatomic phenotype of the patient?

While root resorption has been associated with various factors such as root morphology and use of heavy forces, many of these links remain tenuous (Weltman *et al.*, 2010). 3D images derived from CBCT scans may offer better insights into key causative factors for apical root resorption, particularly if performed at high resolution on a limited FOV. This information would enable clinicians to take necessary measures to minimize damage to roots during orthodontic treatment. Similar studies could help to distinguish the systemic and/or local basis for the mild localized versus moderate to severe generalized root resorption phenotypes that likely have different underlying biologic reasons and, thus, possibly contribute to more refined methods to manage or prevent these adverse responses. Also, a careful assessment of the correlations between 3D changes in root morphology during orthodontic treatment and biomarkers may offer novel non-invasive diagnostic assays that could be used to identify subjects predisposed to or undergoing orthodontic root resorption. This would enable the clinician to make appropriate and timely decisions on treatment options. Additionally, it is possible that high-resolution CBCT scans might offer definitive diagnostic information on tooth ankylosis in the future, which is an important question in need of investigation. Finally, CBCT imaging could help answer numerous questions within the broad thematic areas of orthognathic surgery, CL/P, craniofacial anomalies, developing asymmetries, as well as airway morphology, OSA, and TMJ disorders.

CONCLUSIONS

Since its introduction into dentistry in 1998, CBCT has become an increasingly important source of 3D volumetric information in clinical orthodontics. Over this period, valuable CBCT data have been accumulated on technology assessment, craniofacial morphology in health and disease, treatment outcomes, and efficacy of CBCT images in diagnosis and treatment planning. This chapter provides a summary of the current understanding of and evidence for the clinical utility of CBCT in orthodontics, reviews the findings that use this technology in answering clinically relevant questions, describes the current indications and protocols for the use of CBCT in specific cases, and poses key questions that need to be addressed through additional studies that would help to validate or determine other future uses of this technology in orthodontics. Although CBCT continues to gain substantial popularity, its use currently is recommended in cases in which conventional radiography cannot supply satisfactory diagnostic information including impacted teeth, CL/P, and planning of orthognathic or craniofacial surgery patients. CBCT on other types of cases also can be performed where there is likely to be a positive benefit-to-risk outcome such as supernumerary teeth, identification of root resorption caused by unerupted teeth, evaluating boundary conditions, TMJ degeneration, and progressive bite changes and for placement of TADs in complex situations.

References

Abdul-Kader, H. (2008) Medicolegal perspective: interpretation of pretreatment orthodontic radiographs. *World Journal of Orthodontics*, 9, 14–20.

Adams, G.L., Gansky, S.A., Miller, A.J., *et al*. (2004) Comparison between traditional 2-dimensional cephalometry and a 3-dimensional approach on human dry skulls. *American Journal of Orthodontics and Dentofacial Orthopedics*, 126 (4), 397–409.

Ahmad, M., Hollender, L., Anderson, Q., *et al*. (2009) Research diagnostic criteria for temporomandibular disorders (RDC/TMD): development of image analysis criteria and examiner reliability for image analysis. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 107 (6), 844–860.

Ahmed, F., Brooks, S.L., & Kapila, S. (2012) The efficacy of identifying maxillofacial lesions in cone beam computed tomographs by orthodontists and orthodontic residents. *American Journal of Orthodontics and Dentofacial Orthopedics*, 141, 451–459. http://dx.doi.org/10.1016/j.ajodo.2011.10.025.

Alexiou, K., Stamatakis, H., & Tsiklakis, K. (2009) Evaluation of the severity of temporomandibular joint osteoarthritic changes related to age using cone beam computed tomography. *Dentomaxillofacial Radiology*, 38 (3), 141–147.

Alkhader, M., Ohbayashi, N., Tetsumura, A., *et al*. (2010) Diagnostic performance of magnetic resonance imaging for detecting osseous abnormalities of the temporomandibular joint and its correlation with cone beam computed tomography. *Dentomaxillofacial Radiology*, 39 (5), 270–276.

Allaart, C.F., Goekoop-Ruiterman, Y.P., de Vries-Bouwstra, J.K., *et al*. (2006) Aiming at low disease activity in rheumatoid arthritis with initial combination therapy or initial monotherapy strategies: the BeSt study. *Clinical and Experimental Rheumatology*, 24 (6 Suppl 43), S77–S82.

Almeida, R.C., Cevidanes, L.H., & Carvalho, F.A. (2011) Soft tissue response to mandibular advancement using 3D CBCT scanning. *International Journal of Oral and Maxillofacial Surgery*, 40 (4), 353–359.

Alqerban, A., Jacobs, R., Lambrechts, P., *et al*. (2009a) Root resorption of the maxillary lateral incisor caused by impacted canine: a literature review. *Clinical Oral Investigations*, 13 (3), 247–255.

Alqerban, A., Jacobs, R., Souza, P.C., *et al*. (2009b) *In-vitro* comparison of two cone-beam computed tomography systems and panoramic imaging for detecting simulated canine impaction-induced external root resorption in maxillary lateral incisors. *American Journal of Orthodontics and Dentofacial Orthopedics*, 136 (6), 764, e1–e11.

Alqerban, A., Jacobs, R., & Fieuws, S. (2011a) Comparison of six cone-beam computed tomography systems for image quality and detection of simulated canine impaction-induced external root resorption in maxillary lateral incisors. *American Journal of Orthodontics and Dentofacial Orthopedics*, 140 (3), e129–e139.

Alqerban, A., Jacobs, R., & Fieuws, S. (2011b) Comparison of two cone beam computed tomographic systems versus panoramic imaging for localization of impacted maxillary canines and detection of root resorption. *European Journal of Orthodontics*, 33 (1), 93–102.

American Association of Orthodontists. Statement on the Role of CBCT in Orthodontics (26-10 H). eBulletin May 7, 2010. Available at: http://www.aaomembers.org/Resources/Publications/ebulletin-05-06-10.cfm, accessed March 18, 2011.

American Association of Orthodontists Insurance Company. (2010) Cone beam technology: legal caveats. *The Bulletin*, 28, 24–25.

Artun, J. & Grobety, D. (2001) Periodontal status of mandibular incisors after pronounced orthodontic advancement during adolescence: a follow-up evaluation. *American Journal of Orthodontics and Dentofacial Orthopedics*, 119 (1), 2–10.

Asaumi, J.I., Hisatomi, M., Yanagi, Y., *et al*. (2008) Evaluation of panoramic radiographs taken at the initial visit at a department of paediatric dentistry. *Dentomaxillofacial Radiology*, 37 (6), 340–343.

Avrahami, E. & Englender, M. (1995) Relation between CT axial cross-sectional area of the oropharynx and obstructive sleep apnea syndrome in adults. *American Journal of Neuroradiology*, 16 (1), 135–140.

Baek, S.H., Kim, T.K., & Kim, M.J. (2006) Is there any difference in the condylar position and angulation after asymmetric mandibular setback? *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 101 (2), 155–163.

Baek, S.H., Kim, K., & Choi, J.Y. (2009) Evaluation of treatment modality for skeletal class III malocclusion with labioversed upper incisors and/or protrusive maxilla: surgical movement and stability of rotational maxillary setback procedure. *Journal of Craniofacial Surgery*, 20 (6), 2049–2054.

Baik, H.S. & Kim, S.Y. (2010) Facial soft-tissue changes in skeletal Class III orthognathic surgery patients analyzed with 3-dimensional laser scanning. *American Journal of Orthodontics and Dentofacial Orthopedics*, 138 (2), 167–178.

Berlin, L. (2005) Errors of omission. *American Journal of Roentgenology*, 185 (6), 1416–1421.

Bondemark, L., Jeppsson, M., Lindh-Ingildsen, L., *et al*. (2006) Incidental findings of pathology and abnormality in pretreatment orthodontic panoramic radiographs. *Angle Orthodontist*, 76 (1), 98–102.

Botticelli, S., Verna, C., Cattaneo, P.M., *et al*. (2011) Two- versus three-dimensional imaging in subjects with unerupted maxillary canines. *European Journal of Orthodontics*, 33 (4), 344–349.

Bouwens, D.G., Cevidanes, L., Ludlow, J.B., *et al*. (2011) Comparison of mesiodistal root angulation with posttreatment panoramic radiographs and cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 139 (1), 126–132.

Brooks, S.L. (2009) CBCT dosimetry: orthodontic considerations. *Seminars in Orthodontics*, 15 (1), 14–18.

Busby, B.R., Bailey, L.J., Proffit, W.R., *et al*. (2002) Long-term stability of surgical class III treatment: a study of 5-year postsurgical results. *The International Journal of Adult Orthodontics and Orthognathic Surgery*, 17 (3), 159–170.

Caballero, P., Alvarez-Sala, R., Garcia-Rio, F., *et al*. (1998) CT in the evaluation of the upper airway in healthy subjects and in patients with obstructive sleep apnea syndrome. *Chest*, 113 (1), 111–116.

Caglayan, F. & Tozoglu, U. (2012) Incidental findings in the maxillofacial region detected by cone beam CT. *Diagnostic and Interventional Radiology*, 18 (2), 159–163.

Carvalho Fde, A., Almeida, R.C., Almeida, M.A., *et al*. (2010) Efficiency of light-emitting diode and halogen units in reducing residual monomers. *American Journal of Orthodontics and Dentofacial Orthopedics*, 138 (5), 617–622.

Cattaneo, P.M., Treccani, M., Carlsson, K., *et al*. (2011) Transversal maxillary dento-alveolar changes in patients treated with active and passive self-ligating brackets: a randomized clinical trial using CBCT-scans and digital models. *Orthodontics & Craniofacial Research*, 14 (4), 222–233.

Cevidanes, L.H., Bailey, L.J., Tucker, G.R., Jr., *et al*. (2005) Superimposition of 3D cone-beam CT models of orthognathic surgery patients. *Dentomaxillofacial Radiology*, 34 (6), 369–375.

Cevidanes, L.H., Bailey, L.J., Tucker, S.F., *et al*. (2007) Three-dimensional cone-beam computed tomography for assessment of mandibular changes after orthognathic surgery. *American Journal of Orthodontics and Dentofacial Orthopedics*, 131 (1), 44–50.

Cevidanes, L.H., Hajati, A.K., Paniagua, B., *et al*. (2010a) Quantification of condylar resorption in temporomandibular joint osteoarthritis. *Oral Surgery, Oral Medicine, Oral Pathololology, Oral Radiolology and Endodontology*, 110 (1), 110–117.

Cevidanes, L.H., Motta, A., Proffit, W.R., *et al*. (2010b) Cranial base superimposition for 3-dimensional evaluation of soft-tissue changes. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4 Suppl), S120–S129.

Cha, J.Y., Mah, J., & Sinclair, P. (2007) Incidental findings in the maxillofacial area with 3-dimensional cone-beam imaging. *American Journal of Orthodotics and Dentofacial Orthopedics*, 132 (1), 7–14.

Chen, F., Terada, K., Hua, Y., *et al*. (2007) Effects of bimaxillary surgery and mandibular setback surgery on pharyngeal airway measurements in patients with Class III skeletal deformities. *American Journal of Orthodontics and Dentofacial Orthopedics*, 131 (3), 372–377.

Corbridge, J.K., Campbell, P.M., Taylor, R., *et al*. (2011) Transverse dentoalveolar changes after slow maxillary expansion. *American Journal of Orthodontics and Dentofacial Orthopedics*, 140 (3), 317–325.

Dalstra, M., Cattaneo, P.M., & Melsen, B. (2004) Load transfer of miniscrews for orthodontic anchorage. *Orthodontics*, 1, 53–62.

Degerliyurt, K., Ueki, K., Hashiba, Y., *et al*. (2008) A comparative CT evaluation of pharyngeal airway changes in class III patients receiving bimaxillary surgery or mandibular setback surgery. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 105 (4), 495–502.

Draenert, F.G., Erbe, C., Zenglein, V., *et al*. (2010) 3D analysis of condylar position after sagittal split osteotomy of the mandible in mono- and bimaxillary orthognathic surgery: a methodology study in 18 patients. *Journal of Orofacial Orthopedics*, 71 (6), 421–429.

Dudic, A., Giannopoulou, C., Leuzinger, M., *et al*. (2009) Detection of apical root resorption after orthodontic treatment by using panoramic radiography and cone-beam computed tomography of super-high resolution. *American Journal of Orthodontics and Dentofacial Orthopedics*, 135 (4), 434–437.

Durack, C., Patel, S., Davies, J., *et al*. (2011) Diagnostic accuracy of small volume cone beam computed tomography and intraoral periapical radiography for the detection of simulated external inflammatory root resorption. *International Endodontic Journal*, 44 (2), 136–147.

Farman, A.G. & Scarfe, W.C. (2006) Development of imaging selection criteria and procedures should precede cephalometric assessment with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 130 (2), 257–265.

Finzel, S., Rech, J., Schmidt, S., *et al*. (2011) Repair of bone erosions in rheumatoid arthritis treated with tumour necrosis factor inhibitors is based on bone apposition at the base of the erosion. *Annals of the Rheumatic Diseases*, 70 (9), 1587–1593.

Friedland, B. (2009) Medicolegal issues related to cone-beam CT. *Semininars in Orthodontics*, 15 (1), 77–84.

Fuhrmann, R. (1996) Three-dimensional interpretation of periodontal lesions and remodeling during orthodontic treatment: part III. *Journal of Orofacial Orthopedics*, 57 (4), 224–237.

Galvin, J.R., Rooholamini, S.A., & Stanford, W. (1989) Obstructive sleep apnea: diagnosis with ultrafast CT. *Radiology*, 171 (3), 775–778.

Garcia Silva, M.A., Wolf, U., Heinicke, F., *et al*. (2008a) Cone-beam computed tomography for routine orthodontic treatment planning: a radiation dose evaluation. *American Journal of Orthodontics and Dentofacial Orthopedics*, 133 (640), e1–e5.

Garcia Silva, M.A., Wolf, U., Heinicke, F., *et al*. (2008b) Effective dosages for recording Veraviewepocs dental panoramic images: analog film, digital, and panoramic scout for CBCT. *Oral Surgery Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 106 (4), 571–577.

Garcia-Figueroa, M.A., Raboud, D.W., Lam, E.W., *et al*. (2008) Effect of buccolingual root angulation on the mesiodistal angulation shown on panoramic radiographs. *American Journal of Orthodontics and Dentofacial Orthopedics*, 134 (1), 93–99.

Garib, D.G., Yatabe, M.S., Ozawa, T.O., *et al*. (2012) Alveolar bone morphology in patients with bilateral complete cleft lip and palate in the mixed dentition: cone beam computed tomography evaluation. *The Cleft Palate-Craniofacial Journal*, 49 (2), 208–214.

Garrett, B.J., Caruso, J.M., Rungcharassaeng, K., *et al*. (2008) Skeletal effects to the maxilla after rapid maxillary expansion assessed with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 134 (1), 8–9.

Gateno, J., Teichgraeber, J.F., & Xia, J.J. (2003) Three-dimensional surgical planning for maxillary and midface distraction ostogenesis. *The Journal of Craniofacial Surgery*, 14 (6), 833–839.

Gateno, J., Xia, J.J., & Teichgraeber, J.F. (2007) Clinical feasibility of computer-aided surgical simulation (CASS) in the treatment of complex cranio-maxillofacial deformities. *Journal of Oral and Maxillofacial Surgery*, 65 (4), 728–734.

Gracco, A., Lombardo, L., Cozzani, M., *et al*. (2008) Quantitative cone-beam computed tomography evaluation of palatal bone thickness for orthodontic miniscrew placement. *American Journal of Orthodontics and Dentofacial Orthopedics*, 134 (3), 361–369.

Guyuron, B. (1988) Facial deformity with juvenile rheumatoid arthritis. *Plastic and Reconstructive Surgery*, 81 (6), 948–951.

Gynther, G.W., Tronje, G., & Holmlund, A.B. (1996) Radiographic changes in the temporomandibular joint in patients with generalized osteoarthritis and rheumatoid arthritis. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 81 (5), 613–618.

Hamada, Y., Kondoh, T., Noguchi, K., *et al*. (2005) Application of limited cone beam computed tomography to clinical assessment of alveolar bone grafting: a preliminary report. *Cleft Palate and Craniofacial Journal*, 42 (2), 128–137.

Haney, E., Gansky, S.A., Lee, J.S., *et al*. (2010) Comparative analysis of traditional radiographs and cone-beam computed tomography volumetric images in the diagnosis and treatment planning of maxillary impacted canines. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (5), 590–597.

Haponik, E.F., Smith, P.L., Bohlman, M.E., *et al*. (1983) Computerized tomography in obstructive sleep apnea: correlation of airway size with physiology during sleep and wakefulness. *American Review of Respiratory Disease*, 127 (2), 221–226.

Hassfeld, S. & Muhling, J. (2001) Computer assisted oral and maxillofacial surgery: a review and an assessment of technology. *International Journal of Oral and Maxillofacial Surgery*, 30 (1), 2–13.

Helenius, L.M., Hallikainen, D., Helenius, I., *et al*. (2005) Clinical and radiographic findings of the temporomandibular joint in patients with various rheumatic diseases: a case control study. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 99 (4), 455–463.

Honda, K., Larheim, T.A., Maruhashi, K., *et al*. (2006) Osseous abnormalities of the mandibular condyle: diagnostic reliability of cone beam computed tomography compared with helical computed tomography based on an autopsy material. *Dentomaxillofacial Radiology*, 35 (3), 152–157.

Honey, O.B., Scarfe, W.C., Hilgers, M.J., *et al*. (2007) Accuracy of cone-beam computed tomography imaging of the temporomandibular joint: comparisons with panoramic radiology and linear tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 132 (4), 429–438.

Hong, J.S., Park, Y.H., Kim, Y.J., *et al*. (2011) Three-dimensional changes in pharyngeal airway in skeletal Class III patients undergoing orthognathic surgery. *Journal of Oral and Maxillofacial Surgery*, 69 (11), e401–e408.

Honrado, C.P., Lee, S., Bloomquist, D.S., *et al*. (2006) Quantitative assessment of nasal changes after maxillomandibular surgery using a 3-dimensional digital imaging system. *Archives of Facial Plastic Surgery*, 8 (1), 26–35.

ICRP, International Commission on Radiological Protection. (1991) The 1990 recommendations of the International Commission on Radiological Protection, publication 60. *Annals of ICRP*, 21, 1–201.

ICRP, International Commission on Radiological Protection. (2008) The 2007 recommendations of the International Commission on Radiological Protection, publication 103. *Annals of ICRP*, 37, 1–332.

Isaacson, K.G., Thom, A.R., Horner, K., *et al*. (2008) *Orthodontic Radiographs: Guidelines*, 3rd ed. British Orthodontic Society, London.

Jakobsone, G., Stenvik, A., Sandvik, L., *et al*. (2011) Three-year follow-up of bimaxillary surgery to correct skeletal Class III malocclusion: stability and risk factors for relapse. *American Journal of Orthodontics and Dentofacial Orthopedics*, 139 (1), 80–89.

Johnson, D.P. (2011) Effects of curve of Wilson correction and pre-treatment boundary conditions on quantitative changes in alveolar bone morphology. Master of Science thesis, The University of Michigan.

Jung, B.A., Wehrbein, H., Wagner, W., *et al*. (2012) Preoperative diagnostic for palatal implants: is CT or CBCT necessary? *Clinical Implant Dentistry and Related Research*, 14 (3), 400–405.

Jung, Y.J., Kim, M.J., & Baek, S.H. (2009) Hard and soft tissue changes after correction of mandibular prognathism and facial asymmetry by mandibular setback surgery: three-dimensional analysis using computerized tomography. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 107 (6), 763–771, e8.

Kapila, S. & Farman, A.G. (2003) Craniofacial imaging in the 21st century. Proceedings of the 2002 COAST conference, Asilomar Conference Center, Pacific Grove, California. *Orthodontics and Craniofacial Research*, 6 (Suppl 1).

Kapila, S., Conley, R.S., & Harrel, W. (2011) Current status of cone beam computed tomography imaging in orthodontics. *Journal of Dentomaxillofacial Radiology*, 40 (1), 24–34. http://dx.doi.org/10.1259/dmfr/12615645.

Kartalian, A., Gohl, E., Adamian, M., *et al*. (2010) Cone-beam computerized tomography evaluation of the maxillary dentoskeletal complex after rapid palatal expansion. *American Journal of Orthodontics and Dentofacial Orthopedics*, 138 (4), 486–492.

Katheria, B.C., Kau, C.H., Tate, R., *et al*. (2010) Effectiveness of impacted and supernumerary tooth diagnosis from traditional radiography versus cone beam computed tomography. *Pediatric Dentistry*, 32 (4), 304–309.

Katsumata, A., Hirukawa, A., Noujeim, M., *et al*. (2006) Image artifact in dental cone-beam CT. *Oral Surgery, Oral Medicine, Oral Pathololgy, Oral Radiology and Endodontology*, 101 (5), 652–657.

Katsumata, A., Hirukawa, A., Okumura, S., *et al*. (2007) Effects of image artifacts on gray-value density in limited-volume cone-beam computerized tomography. *Oral Surgery, Oral Medicine, Oral Pathololgy, Oral Radiology and Endodontology*, 104 (6), 829–836.

Kau, C.S., Richmond, J., Palomo, M., *et al*. (2005) Current products and practice: three dimensional cone beam computerized tomography in orthodontics. *Journal of Orthodontics*, 32 (4), 282–293.

Kim, B.R., Oh, K.M., Cevidanes, L.H., *et al*. (2013) Analysis of 3D soft tissue changes after 1- and 2-jaw orthognathic surgery in mandibular prognathism patients. *Journal of Oral and Maxillofacial Surgery*, 71 (1), 151–161.

Kim, Y.I., Jung, Y.H., Cho, B.H., *et al*. (2010) The assessment of the short and long-term changes in the condylar position following sagittal split ramus osteotomy (SSRO) with rigid fixation. *Journal of Oral Rehabilitation*, 37 (4), 262–270.

Kim, Y.I., Cho, B.H., Jung, Y.H., *et al*. (2011) Cone-beam computerized tomography evaluation of condylar changes and stability following two-jaw surgery: Le Fort I osteotomy and mandibular setback surgery with rigid fixation. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 111 (6), 681–687.

Kim, Y.J., Oh, K.M., Hong, J.S., *et al*. (2012) Do patients treated with bimaxillary surgery have more stable condylar positions than those who have undergone single-jaw surgery? *Journal of Oral and Maxillofacial Surgery*, 70 (9), 2143–2152.

King, K.S., Lam, E.W., Faulkner, M.G., *et al*. (2007) Vertical bone volume in the paramedian palate of adolescents: a computed tomography study. *American Journal of Orthodontics and Dentofacial Orthopedics*, 132 (6), 783–788.

Korbmacher, H., Kahl-Nieke, B., Schollchen, M., *et al*. (2007) Value of two cone-beam computed tomography systems from an orthodontic point of view. *Journal of Orofacial Orthopedics*, 68 (4), 278–289.

Koyama, J., Nishiyama, H., & Hayashi, T. (2007) Follow-up study of condylar bony changes using helical computed tomography in patients with temporomandibular disorder. *Dentomaxillofacial Radiology*, 36 (8), 472–477.

Kuhlberg, A.J. & Norton, L.A. (2003) Pathologic findings in orthodontic radiographic images. *American Journal of Orthodontics and Dentofacial Orthopedics*, 123 (2), 182–184.

Kumar, V., Ludlow, J., Cevidanes, L.H., *et al*. (2008) *In vivo* comparison of conventional and cone beam CT synthesized cephalograms. *The Angle Orthodontist*, 78 (5), 873–879.

Lee, W. & Park, J.U. (2002) Three-dimensional evaluation of positional change of the condyle after mandibular setback by means of bilateral sagittal split ramus osteotomy. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 94 (3), 305–309.

Lenza, M.G., Lenza, M.M., Dalstra, M., *et al*. (2010) An analysis of different approaches to the assessment of upper airway morphology: a CBCT study. *Orthodontics & Craniofacial Research*, 13 (2), 96–105.

Leung, C.C., Palomo, L., Griffith, R., *et al*. (2010) Accuracy and reliability of cone-beam computed tomography for measuring alveolar bone height and detecting bony dehiscences and fenestrations. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (Suppl 4), S109–S119.

Lim, Y.K., Chu, E.H., Lee, D.Y., *et al*. (2010) Three-dimensional evaluation of soft tissue change gradients after mandibular setback surgery in skeletal Class III malocclusion. *The Angle Orthodontist*, 80 (5), 896–903.

Loubele, M., Jacobs, R., Maes, F., *et al*. (2005) Radiation dose vs. image quality for low-dose CT protocols of the head for maxillofacial surgery and oral implant planning. *Radiation Protection Dosimetry*, 117 (1–3), 211–216.

Ludlow, J.B. (2009a) Dosimetry of small FOV tomography using OP 200 VT & Scanora 3D. 60th annual session of the American Academy of Oral and Maxillofacial Radiology (AAOMR), Louisville, KY, October 22.

Ludlow, J.B. (2009b) Dose and risk in dental diagnostic imaging with emphasis on dosimetry of CBCT. *Korean Journal of Oral and Maxillofacial Radiology*, 39 (4), 175–184.

Ludlow, J.B. & Ivanovic, M. (2008) Comparative dosimetry of dental CBCT devices and 64 row CT for oral and maxillofacial radiology. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 106 (1), 930–938.

Ludlow, J.B., Davies-Ludlow, L.E., & White, S.C. (2008) Patient risk to common dental radiographic examinations: the impact of 2007 ICRP recommendations regarding dose calculation. *Journal of the American Dental Association*, 139 (9), 1237–1243.

Lund, H., Gröndahl, K., & Gröndahl, H.G. (2010) Cone beam computed tomography for assessment of root length and marginal bone level during orthodontic treatment. *The Angle Orthodontist*, 80 (3), 466–473.

Magalhaes, A.E., Stella, J.P., & Tahasuri, T.H. (1995) Changes in condylar position following bilateral sagittal split ramus osteotomy with setback. *International Journal of Adult Orthodontics and Orthognathic Surgery*, 10 (2), 137–145.

Marquezan, M., Lau, T.C., Mattos, C.T., *et al*. (2012) Bone mineral density. *The Angle Orthodontist*, 82 (1), 62–66.

McCance, A.M., Moss, J.P., Fright, W.R., *et al*. (1992) A three dimensional analysis of soft and hard tissue changes following bimaxillary orthognathic surgery in skeletal III patients. *British Journal of Oral and Maxillofacial Surgery*, 30 (5), 305–312.

McKee, I.W., Williamson, P.C., Lam, E.W., *et al*. (2002) The accuracy of four panoramic units in the projection of mesiodistal tooth angulations. *American Journal of Orthodontics and Dentofacial Orthopedics*, 121 (2), 166–175.

Metzger, M.C., Hohlweg-Majert, B., Schon, R., *et al*. (2007) Verification of clinical precision after computer-aided reconstruction in craniomaxillofacial surgery. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 104 (4), e1–e10.

Miles, D.A. (2005) Clinical experience with cone-beam volumetic imaging: report of findings in 381 cases. *Computed Tomography*, 20, 416–424.

Miles, D.A. (2009) Interpreting the cone beam data volume for occult pathology. *Seminars in Orthodontics*, 15, 70–76.

Miracle, A.C. & Mukherji, S.K. (2009) Conebeam CT of the head and neck. Part 1: physical principles. *American Journal of Neuroradiolology*, 30 (6), 1088–1095.

Molen, A.D. (2010) Considerations in the use of cone-beam computed tomography for buccal bone measurements. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), S130–S135.

Molen, A.D. (2011) Comparing cone-beam computed tomography systems from an orthodontic perspective. *Seminars in Orthodontics*, 17 (1), 34–38.

Motta, A.T., Cevidanes, L.H., Carvalho, L.H., *et al*. (2011) Three-dimensional regional displacements after mandibular advancement surgery: one year of follow-up. *Journal of Oral and Maxillofacial Surgery*, 69 (5), 1447–1457.

Mozzo, P., Poracci, C., Tacconi, A., *et al*. (1998) A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *European Radiology*, 8 (9), 1558–1564.

Mucedero, M., Coviello, A., Baccetti, T., *et al*. (2008) Stability factors after double-jaw surgery in Class III malocclusion: a systematic review. *The Angle Orthodontist*, 78 (6), 1141–1152.

Nair, M.K., Pettigrew, J.C., Jr., & Mancuso, A.A. (2007) Intracranial aneurysm as an incidental finding. *Dentomaxillofacial Radiolology*, 36 (2), 107–112.

Oberoi, S., Chigurupati, R., Gill, P., *et al*. (2009) Volumetric assessment of secondary alveolar bone grafting using cone beam computed tomography. *The Cleft Palate–Craniofacial Journal*, 46 (5), 503–511.

Oberoi, S., Gill, P., Chigurupati, R., *et al*. (2010) Three-dimensional assessment of the eruption path of the canine in individuals with bone-grafted alveolar clefts using cone beam computed tomography. *The Cleft Palate–Craniofacial Journal*, 47 (5), 507–512.

Okano, T., Harata, Y., Sugihara, Y., *et al*. (2009) Absorbed and effective doses from cone beam volumetric imaging for implant planning. *Dentomaxillofacial Radiolology*, 38, 79–85.

Okeson, J.P. (1996) *Orofacial Pain: Guidelines for Assessment, Diagnosis and Management. American Academy of Orofacial Pain*. Quintessence, Chicago, IL.

Oliviera de Felippe, N.L., Da Silveira, A.C., Viana, G., *et al*. (2008) Relationship between rapid maxillary expansion and nasal cavity size and airway resistance: short- and long-term effects. *American Journal of Orthodontics and Dentofacial Orthopedics*, 134 (3), 370–382.

Oransky, I. (2004) Sir Godfrey N. Hounsfield. *Lancet*, 364 (9439), 1032.

Owens, A.M. & Johal, A. (2008) Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. *The Angle Orthodontist*, 78 (3), 475–481.

Palomo, J.M., Rao, P.S., & Hans, M.G. (2008) Influence of CBCT exposure conditions on radiation dose. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 105 (6), 773–782.

Paniagua, B., Cevidanes, L., Zhu, H., *et al*. (2010) Outcome quantification using SPHARM-PDM toolbox in orthognathic surgery. *International Journal of Computer Assisted Radiology and Surgery*, 6 (5), 617–626.

Park, S.B., Yoon, J.K., Kim, Y.I., *et al*. (2012) The evaluation of the nasal morphologic changes after bimaxillary surgery in skeletal Class III maloccusion by using the superimposition of cone-beam computed tomography (CBCT) volumes. *Journal of Craniomaxillofacial Surgery*, 40 (4), e87–e92.

Patcas, R., Muller, L., Ullrich, O., *et al*. (2012) Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth. *American Journal of Orthodontics and Dentofacial Orthopedics*, 141 (1), 41–50.

Peck, J.L., Sameshima, G.T., Miller, A., *et al*. (2007) Mesiodistal root angulation using panoramic and cone beam CT. *The Angle Orthodontist*, 77 (2), 206–213.

Periago, D.R., Scarfe, W.C., Moshiri, M., *et al*. (2008) Linear accuracy and reliability of cone beam CT derived 3-dimensional images constructed using an orthodontic volumetric rendering program. *The Angle Orthodontist*, 78 (3), 387–395.

Ponder, S., Benavides, E., Kapila, S., *et al*. (2012) Quantification of external root resorption by low- vs. high-resolution cone beam computed tomography and periapical radiography: a volumetric and linear analysis. *American Journal of Orthodontics and Dentofacial Orthopedics*, 143 (6), 77–91.

Popat, H., Drage, N., & Durning, P. (2008) Mid-line clefts of the cervical vertebrae: an incidental finding arising from cone beam computed tomography of the dental patient. *British Dental Journal*, 204 (6), 303–306.

Price, J.B., Thaw, K.L., Tyndall, D.A., *et al*. (2012) Incidental findings from cone beam computed tomography of the maxillofacial region: a descriptive retrospective study. *Clinical Oral Implants Research*, 23 (11), 1261–1268.

Proffit, W.R., Turvey, T.A., & Phillips, C. (2007) The hierarchy of stability and predictability in orthognathic surgery with rigid fixation: an update and extension. *Head & Face Medicine*, 3, 21.

Quereshy, F.A., Barnum, G., Demko, C., *et al*. (2011) Use of cone beam computed tomography to volumetrically assess alveolar cleft defects: preliminary results.

Journal of Oral and Maxillofacial Surgery, 70 (1), 188–191.

Quintero, J., Trosien, A., Hatcher, D., *et al*. (1999) Craniofacial imaging in orthodontics: historical perspective, current status, and future developments. *The Angle Orthodontist*, 69 (6), 491–506.

Raju, T.N. (1999) The Nobel chronicles. 1979: Allan MacLeod Cormack (b 1924) and Sir Godfrey Newbold Hounsfield (b 1919). *Lancet*, 354 (9190), 1653.

Ren, H., Chen, J., Deng, F., *et al*. (2012) Comparison of cone-beam computed tomography and periapical radiography for detecting simulated apical root resorption. *The Angle Orthodontist*, 83 (2), 189–195.

Renfrew, D., Franken, E.A., Jr., Berbaum, K.S., *et al*. (1992) Error in radiology: classification and lessons in 182 cases presented at a problem conference. *Radiology*, 183 (1), 145–150.

Rogers, S.A., Drage, N., & Durning, P. (2011) Incidental findings arising with cone beam computed tomography imaging of the orthodontic patient. *The Angle Orthodontist*, 81 (2), 350–355.

Rungcharassaeng, K., Caruso, J.M., Kan, J.Y., *et al*. (2007) Factors affecting buccal bone changes of maxillary posterior teeth after rapid maxillary expansion. *American Journal of Orthodontics and Dentofacial Orthopedics*, 132 (4), 428, e1-e8.

Ryckman, M.S., Harrison, S., Oliver, D., *et al*. (2010) Soft-tissue changes after maxillomandibular advancement surgery assessed with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), S86–S93.

Samman, N., Tong, A.C., Cheung, D.L., *et al*. (1992) Analysis of 300 dentofacial deformities in Hong Kong. *International Journal of Adult Orthodontics and Orthognathic Surgery*, 7 (3), 181–185.

Sarikaya, S., Haydar, B., Ciger, S., *et al*. (2002) Changes in alveolar bone thickness due to retraction of anterior teeth. *American Journal of Orthodontics and Dentofacial Orthopedics*, 122 (1), 15–26.

Schendel, S.A. & Hatcher, D. (2010) Automated 3-dimensional airway analysis from cone-beam computed tomography data. *Journal of Oral and Maxillofacial Surgery*, 68 (3), 696–701.

Schwab, R.J., Pasirstein, M., Pierson, R., *et al*. (2003) Identification of upper airway anatomic risk factors for obstructive sleep apnea with volumetric magnetic resonance imaging. *American Journal of Respiratory and Critical Care Medicine*, 168 (5), 522–530.

Segal, G.R., Schiffman, P.H., & Tuncay, O.C. (2004) Meta-analysis of the treatment-related factors of external apical root resorption. *Orthodontics and Craniofacial Research*, 7 (2), 71–78.

SEDENTEXCT Guideline Development Panel. (May 2009) Radiation Protection: Cone Beam CT for Dental and Maxillofacial Radiology Provisional Guidelines 2009 (v. 1.1 May 2009). Available at: http://www.sedentexct.eu, accessed June 10, 2013.

SEDENTEXCT Guideline Development Panel. (2011) Radiation Protection: Cone Beam CT for Dental and Maxillofacial Radiology: Evidence Based Guidelines 2011 (v. 2.0 Final). Available at: http://www.sedentexct.eu, accessed June 10, 2013.

Sherrard, J.F., Rossouw, P.E., Benson, B.W., *et al*. (2010) Accuracy and reliability of tooth and root lengths measured on cone-beam computed tomographs. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), S100–S108.

Shirota, T., Kurabayashi, H., Ogura, H., *et al*. (2010) Analysis of bone volume using computer simulation system for secondary bone graft in alveolar cleft. *International Journal of Oral and Maxillofacial Surgery*, 39 (9), 904–908.

Silva, M.A., Wolf, U., Heinicke, F., *et al*. (2008) Cone-beam computed tomography for routine orthodontic treatment planning: a radiation dose evaluation. *American Journal of Orthodontics and Dentofacial Orthopedics*, 133 (5), 640, e1-e5.

Smith, J.M. (2009) The normal adult airway in 3-dimensions: a cone-beam computed tomography evaluation establishing normative values. MS thesis, University of Michigan.

Soncul, M. & Bamber, M.A. (2004) Evaluation of facial soft tissue changes with optical surface scan after surgical correction of Class III deformities. *Journal of Oral and Maxillofacial Surgery*, 62 (11), 1331–1340.

Stratemann, S.A., Huang, J.C., Maki, K., *et al*. (2008) Comparison of cone beam computed tomography imaging with physical measures. *Dentomaxillofacial Radiology*, 37 (2), 80–93.

Stratemann, S.A., Huang, J.C., Maki, K., *et al*. (2010) Evaluating the mandible with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), S58–S70.

Suomalainen, A., Kiljunen, T., Käser, Y., *et al*. (2009) Dosimetry and image quality of four dental cone beam computed tomography scanners compared with multislice computed tomography scanners. *Dentomaxillofacial Radiology*, 38 (6), 367–378.

Swennen, G.R. & Schutyser, F. (2006) Three-dimensional cephalometry: spiral multislice vs. cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 130 (3), 410–416.

Tai, K., Hotokezaka, H., Park, J.H., *et al*. (2010a) Preliminary cone-beam computed tomography study evaluating dental and skeletal changes after treatment with a mandibular Schwarz appliance. *American Journal of Orthodontics and Dentofacial Orthopedics*, 138 (3), 262, e1–e11.

Tai, K., Park, J.H., Mishima, K., *et al*. (2010b) Using superimposition of 3-dimensional cone-beam computed tomography images with surface-based registration in growing patients. *Journal of Clinical Pediatric Dentistry*, 34 (4), 361–367.

Tetradis, S. & Kantor, M.L. (1999) Prevalence of skeletal and dental anomalies and normal variants seen in cephalometric and other radiographs of orthodontic patients. *American Journal of Orthodontics and Dentofacial Orthopedics*, 116 (5), 572–577.

Theodorakou, C., Walker, A., Horner, K., *et al*. (2012) Estimation of paediatric organ and effective doses from dental cone beam CT using anthropomorphic phantoms. *British Journal of Radiology*, 85 (1010), 153–160.

Troulis, M.J., Everett, P., Seldin, E.B., *et al*. (2002) Development of a three-dimensional treatment planning system based on computer tomographic data. *International Journal of Oral and Maxillofacial Surgery*, 31 (4), 349–357.

Tsao, D.H., Kazanoglu, A., & McCasland, J.P. (1983) Measurability of radiographic images. *American Journal of Orthodontics and Dentofacial Orthopedics*, 84 (3), 212–216.

Turpin, D. (2007) Befriend your oral and maxillofacial radiologist. *American Journal of Orthodontics and Dentofacial Orthopedics*, 131 (6), 697.

Van Elslande, D., Heo, G., Flores-Mir, C., *et al*. (2010) Accuracy of mesiodistal root angulation projected by cone-beam computed tomographic panoramic-like images. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), S94–S99.

Vannier, M.W. (2003) Craniofacial computed tomography scanning: technology, applications and future trends. *Orthodontics and Craniofacial Research*, 6 (Suppl 1), 23–30.

Walker, L., Enciso, R., & Mah, J. (2005) Three-dimensional localization of maxillary canines with cone-beam computed tomography. *American Journal of Orthodontics and Dentofacial Orthopedics*, 128 (4), 418–423.

Wechsler, R.J., Spettell, C.M., Kurtz, A.B., *et al*. (1996) Effects of training and experience in interpretation of emergency body CT scans. *Radiology*, 199 (3), 717–720.

Wehrbein, H., Bauer, W., & Diedrich, P. (1996) Mandibular incisors, alveolar bone, and symphysis after orthodontic treatment: a retrospective study. *American Journal of Orthodontics and Dentofacial Orthopedics*, 110 (3), 239–246.

Welmerink, A.D. (2012) Effects of non-extraction orthodontic therapy and boundary conditions on quantitative changes in alveolar bone morphology. Master of Science thesis, University of Michigan.

Weltman, B., Vig, K.W., Fields, H.W., *et al*. (2010) Root resorption associated with orthodontic tooth movement: a systematic review. *American Journal of Orthodontics and Dentofacial Orthopedics*, 137 (4), 462–476.

Wilmes, B., Rademacher, C., Olthoff, G., *et al*. (2006) Parameters affecting primary stability of orthodontic mini-implants. *Journal of Orofacial Orthopedics*, 67 (3), 162–174.

Xia, J., Ip, H.H., Samman, N., *et al*. (2000a) Computer-assisted three-dimensional surgical planning and simulation: 3D virtual osteotomy. *International Journal of Oral and Maxillofacial Surgery*, 29 (1), 11–17.

Xia, J., Samman, N., Yeung, R.W., *et al*. (2000b) Three-dimensional virtual reality surgical planning and simulation workbench for orthognathic surgery. *International Journal of Oral and Maxillofacial Surgery*, 15 (4), 265–282.

Yucel, A., Unlu, M., Haktanir, A., *et al*. (2005) Evaluation of the upper airway cross-sectional area changes in different degrees of severity of obstructive sleep apnea syndrome: cephalometric and dynamic CT study. *American Journal of Neuroradiology*, 26 (10), 2624–2629.

Yura, S., Ooi, K., Kadowaki, S., *et al*. (2010) Magnetic resonance imaging of the temporomandibular joint in patients with skeletal open bite and subjects with no dentofacial abnormalities. *British Journal of Oral and Maxillofacial Surgery*, 48 (6), 459–461.

Zhang, W., Shen, G., Wang, X., *et al*. (2012) Evaluation of alveolar bone grafting using limited cone beam computed tomography. *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology*, 113 (4), 542–548.

Zhou, W., Li, W., Lin, J., *et al*. (2013) Tooth lengths of the permanent upper incisors in patients with cleft lip and palate determined with cone beam computed tomography. *Cleft Palate–Craniofacial Journal*, 50 (1), 88–95.

Zinman, E.J., White, S.C., & Tetradis, S. (2010) Legal considerations in the use of cone beam computer tomography imaging. *Journal of the California Dental Association*, 38 (1), 49–56.