There have been recent advances in three-dimensional (3-D) imaging. In this article, we reflect on current practices in orthodontics and how the limits of technology have influenced the clinical routine of orthodontists. For example, instead of focusing on the vertical and transverse dimensions, malocclusions generally are described by using anteroposterior terminology (which may seem awkward to a clinician who does not practice orthodontics, because clinical malocclusion is a 3-D manifestation), which may be why most orthodontic appliances are targeted to result in anteroposterior correction. Furthermore, many orthodontic treatment procedures are geared toward resolving conditions that cannot be appraised adequately by using conventional two-dimensional (2-D) radiographs. For example, dentoalveolar limits of tooth movement, particularly in attempts at nonextraction expansion treatments, cannot be determined without 3-D imaging. In addition, many relationships of the craniofacial complex, such as the position of the mandibular condyles in the temporomandibular fossa with respect to the occlusal scheme and the association of airway abnormalities to craniofacial morphology, cannot be evaluated with conventional imaging approaches.

Cone-beam computed tomography (CBCT) can be used in clinical orthodontics and research in many ways. In this article, we focus on practical applications of CBCT that emphasize its importance in comprehensive orthodontic care. These applications include dental development, limits of tooth movement, airway assessment, craniofacial morphology and superimposition.

DENTAL DEVELOPMENT

The development of the primary and permanent dentition is one of the most complicated processes in human development. Comprehensive evaluation of this 3-D process presents a challenge to clinicians who use conventional imaging, particularly if there are deviations in tooth numbers, shapes, sequence and positions (Figure 1). The complexity of dental

ABSTRACT

Background. Comprehensive visualization and records of the craniofacial complex have been goals in orthodontic imaging. These tasks have been performed by means of plaster, photographs and radiographs. These approaches have evolved across time, and cone-beam computed tomography (CBCT) has emerged as a comprehensive imaging modality for orthodontics.

Methods. The authors provide a practical guide for applying CBCT in orthodontics, with an emphasis on situations in which conventional imaging is limited. These situations include dental development, limits of tooth movement, airway assessment, craniofacial morphology and superimposition.

Results. Complexities of the craniofacial complex, dentition and airway present challenges in obtaining conventional images. CBCT has image-fidelity advantages over conventional imaging that can lead to improved visualization.

Conclusions. CBCT is changing orthodontics with respect to clinically assessing patients and is evolving with respect to diagnosis, clinical techniques and outcomes.

Clinical Implications. The clinical value proposition of CBCT is to describe craniofacial anatomy accurately and provide comprehensive information regarding anatomical relationships and individual patient findings for improved diagnosis, treatment planning and prognostication.

Key Words. Cone-beam computed tomography; craniofacial morphology; orthodontics; cephalometry; airway; superimposition.

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development and its variations are mostly lost in a 2-D record. For example, prognostication of impacted maxillary canines with respect to length of treatment and complexity is restricted when clinicians obtain panoramic radiographs. CBCT offers an undistorted view of the dentition that shows the details of individual dental morphology, including intricate features of tooth roots, and missing, supernumerary and anomalous teeth, as well as the 3-D spatial orientation of the teeth and roots. CBCT imaging puts the clinician in a much better position than does conventional imaging to evaluate eruption patterns and their variations. The information provided can help clinicians study the process of dental development and individualized planning for eruption guidance, selective extractions and custom biomechanical approaches. The 3-D views of the dentition are similar to textbook images that show dental development (Figure 2).

Advances in computer software have allowed for the production of interactive digital models (Anato-Model, Anatomage, San Jose, Calif.) from the CBCT data volume (viewable CBCT data). The advantages of using these models include eliminating the need to take impressions, and that during visualization the clinically visible crowns appear with the tooth roots and surrounding alveolar bone (Figure 3). Conventional radiographic imaging, such as panoramic and small dental radiographs, has limitations—such as magnification, distortion, superimposition, limited perspective and lack of resolution—when it is used to visualize root resorption. Root resorption can be observed readily in CBCT images, and the image clarity allows clinicians to classify the type of root resorption. For teeth with multiple roots, resorption can be localized to a specific root. Another advantage is that the occlusal scheme is related to the position of the condyles within the temporomandibular fossa. No other imaging modality offers this feature. Clinicians can view the soft tissues of the face with respect to both the dentition and skeletal structure, and they can compare the occlusal views of the arches with the shape of the alveolus. The accuracy of dental measurements of overjet, overbite and arch length from these virtual models is comparable with that of other digital study models produced from impressions. There is ongoing research and development in the area of manufacturing dental appliances from dental models developed by means of CBCT.

LIMITS OF TOOTH MOVEMENT

The multidimensional nature of volumetric imaging allows for comprehensive visualization of the dentition and recognition of some of the limits of tooth movement. Many situations cannot be visualized by means of traditional orthodontic records. Enostosis, condensing osteitis, dense bone island and focal apical osteopetrosis are radiopaque lesions noted near the apexes of teeth, and they appear to have no causative factors. A high percentage (88 to 100 percent) of these lesions occur in the mandible, and the most common extraoral positions are the pelvis and long bones. These lesions may not be visualized readily on panoramic radiographs, and they can prevent tooth movement (Figure 4). In these

**ABBREVIATION KEY.** CBCT: Cone-beam computed tomography. MRI: Magnetic resonance imaging. OSA: Obstructive sleep apnea. RP: Retropalatal. 3-D: Three-dimensional. 2-D: Two-dimensional.
situations, space closure and the establishment of proper torque may not be possible, and, if biomechanical forces are applied to move the adjacent tooth against the dense lesion, external apical root resorption may result. A more common situation is that of a patient with a deep bite. Common treatments include the use of biteplates to extrude posterior teeth or intrusion arches to intrude the maxillary anterior teeth to reduce the degree of overbite. A cross-sectional view of the incisors can reveal the vertical dimension of bone apical to the maxillary central incisors and the limited space for intrusion (Figure 5). In these situations, extrusion of the posterior teeth to address the deep bite would be a more appropriate treatment and would prevent damage to the apexes of the central incisors against the dense bone of the nasal floor.

AIRWAY ANALYSIS

The causal relationship between airway disorders and malocclusion was described as early as 1935. This relationship is a common cause of malocclusion and leads to the classic appearance of adenoid facies. Perhaps as a result of the lack of diagnostic instruments in this area, the focus on patient airway assessment seems to have subsided until CBCT arrived and aided in the evaluation of airways. The results of a retrospective review of 500 orthodontic patients showed that 18.2 percent of the patients had airway-related problems.

Lateral cephalograms have been used to analyze the airway. Despite the number of studies in this area, the overall strength of these studies is weak, owing to small sample sizes, lack of control participants, inconsistent head positions and poor study designs. As a result, there are no effective anatomical measures from lateral cephalograms that are correlated with sleep apnea. In contrast, use of 3-D imaging (magnetic resonance imaging [MRI]) revealed more specific anatomical findings in patients with apnea. It seems that the predominant factor causing airway movement is the thickness of the lateral pharyngeal muscular walls, as opposed to the fat pads in this area.

Trudo and colleagues studied healthy volunteers during wakefulness and sleep by means of MRI and found a narrowing in the retropalatal (RP) region of the airway owing to posterior movement of the soft palate, thickening of the lateral pharyngeal walls and an increase in tongue oblique distance. Chen and colleagues found that the anteroposterior and lateral diameters of the RP region, as well as the smallest area of the RP region, are significantly smaller in patients with obstructive sleep apnea (OSA). Although the gold standard for diagnosis of OSA is a sleep study, 3-D imaging can be an adjunctive diagnostic tool.

Within the CBCT data, there is distinction between the soft tissue of the pharynx and the airway space. This distinction allows for relatively straightforward segmentation of the airway in the performance of volumetric analysis (Figure 6).
and eliminate the magnification factor even though the x-rays are not parallel. The isotropic images generated by CBCT facilitate visual observations of asymmetries and abnormalities, which can be confirmed by using linear and angular measurement tools included in 3-D imaging software packages. These measurements are reliable and anatomically accurate.19

The CBCT data set can be reformatted to generate a CBCT-reconstructed lateral cephalogram so that conventional measurements can be made and compared with existing 2-D norms. The advantages of using CBCT-reconstructed lateral cephalograms include the ability to digitally reorient the head position in cases in which the patient did not undergo scanning with the proper head position and the ability to enhance the image quality by virtually sculpting away extraneous superimposing skeletal structures that are not relevant to the lateral cephalometric measurement process. In addition, separate images can be created of the left and right sides for assessment of asymmetries. Software developers are starting to incorporate a way to identify anatomical and cephalometric landmarks on the volumetric data set. This is a starting point for the ability to use new anatomical landmarks not visible on 2-D cephalograms and to measure new distances and angles that will give insight into the growth and development of the craniofacial complex (Figure 7). With this possibility in mind, it also is important to think beyond conventional metrics of measuring distances and angles. Using the concept of morphometrics, clinicians can construct a 3-D norm and then superimpose individual 3-D scans on this norm to determine variations and standard deviations (Figure 8). Clinicians can quantify localized differences by using a color-mapping scheme to determine magnitude of difference. Pretreatment and posttreatment superimpositions also can be added to evaluate tooth movement (Figure 9).

Anteroposterior cephalograms are another radiographic tool that can be used to identify transverse asymmetries. However, slight deviations of head position can produce substantially varying results on conventional radiographs. CBCT-reconstructed anteroposterior cephalograms can reorient the head position after the initial scan and have the ability to remove extraneous superimposing structures (for example, vertebrae) for better image clarity.

**SUPERIMPOSITIONS**

Assessing treatment outcomes is important when documenting treatment changes and research. The approach to lateral cephalometric superimposition used by the American Board of Orthodontics20 involves cranial base registration on the outline of the sella turcica and the best fit of the anterior cranial base bony structures, using the lingual curvature of the palate with the best fit on the maxillary bony structures, and registration on the internal cortical outline of the symphysis with the best fit on the mandibular canal for superimposition of the maxilla and mandible, respectively. Clinicians who have performed this type of cephalometric superimposition are aware that it
is a challenging process owing to issues related to image fidelity, landmark selection and identification. Because the method is limited to superimposition of lateral cephalograms, the information is only from the sagittal plane.

The introduction of CBCT allows clinicians to perform superimpositions in three dimensions and has eliminated some of the errors that occur with traditional lateral cephalometric superimposition. Recently, a method for superimposition of CBCT images that does not first require segmentation or landmark selection was developed that is accurate, fast and automatic. Because this method eliminates the need for segmentation and selecting landmarks, the errors associated with these steps are eliminated, thereby reducing the overall cumulative errors. Common weaknesses of many outcomes studies are image fidelity and method errors in the superimposition process, leading to confounding and often conflicting results. The application of CBCT and this new method of assessing treatment outcomes have the potential to settle many controversies in orthodontics, such as the mechanism of functional appliances, nonextraction philosophies, molar distalization, temporomandibular effects and others.

**UTILIZATION ISSUES**

Although CBCT appears to hold promise for advances in research and clinical orthodontics, there is some uncertainty and controversy related to its radiation dose, direct patient benefit and professional guidelines for use. In consideration of a fundamental concept of diagnostic imaging known as the As Low As Reasonably Achievable principle, a clinician has the responsibility of determining if the risks from diagnostic imaging outweigh the benefits of its use in patient care, which suggests that clinicians also must consider the potential harm to the patient if the imaging is inadequate and if a diagnosis or a problem is missed. In addition, imaging should be performed with a valid diagnostic goal. For example, it is common in orthodontics to obtain panoramic radiographs to assess tooth tip positions. However, the literature on this topic has shown that this practice is unreliable and that clinicians using this practice should have intimate knowledge of panoramic distortions and use caution.

Orthodontics involves the use of various radiographic modalities in its diagnostic protocols, ranging from panoramic radiographs and lateral cephalograms to complete series of radiographs. The radiation doses of these modalities and that of CBCT are found in the introduction to this supplement. Although studies of radiation dosimetry are not directly comparable, the exposure from CBCT is within the same range as traditional dental imaging. The combination of traditional dental radiographs, particularly in a complete series, can result in a radiation dose that is substantially higher than that of CBCT. Nevertheless, critics of CBCT seem to focus on the radiation dose to patients who undergo CBCT, although there has been little or no discussion on this topic as it relates to traditional dental imaging.

With respect to the topic of patient benefit, sev-
eral articles describe the application of and rationale for using CBCT, as well as specific measures or diagnostic functions that are possible or improved with 3-D imaging. Investigators have described comprehensive patient analysis and rationale for using CBCT,31-35 including reports of use in academic34 and private practice35 settings. Specific measures and functions of CBCT in clinical activities include more accurate assessment of lower incisor position36; measures of root length and marginal bone level47; management of impacted canines38-41; visualization of upper airways,42 including a report of substantial incidental findings of airway abnormalities in orthodontic patients13; evaluation of bone dehiscence and fenestration7; measurement of the dentition7 and tooth volume,49 conclusions treated by means of conventional imaging, there was criticism that CBCT has no proven benefit in orthodontics.45 However, reports of orthodontic complications treated by means of conventional imaging are published rarely.46 Case reports have been published recently that show discrepancies between panoramic radiographs and CBCT images in individual cases47 and for the assessment of root contact.48 The therapeutic benefits of CBCT include measurement of the dentition7 and tooth volume,49 planning and evaluation of temporary anchorage devices,19,50-52 monitoring of alveolar bone density and height in interdisciplinary periodontal and orthodontic treatment,53-55 3-D treatment simulation54 and use in appliance manufacturing.55 Most of these activities can be performed in one imaging session with a radiation dose that is in the same range as that of conventional images, which do not provide the same amount of data.

In 2010, the House of Delegates of the American Association of Orthodontists adopted a resolution that states: “RESOLVED, that the AAO recognizes that while 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.”56 Although this resolution is intended to protect the public and provide guidance to clinicians, this statement has created a difficult situation in the acknowledgment of a routine patient. The criteria for classifying a patient as routine are not defined, and the necessary diagnostic protocols to determine if a patient is routine also are undefined. In practice, it would be impossible to determine if a patient is routine without conducting a comprehensive evaluation. Rather, a more practicable guideline would be that CBCT is indicated for comprehensive orthodontic treatment for which precise knowledge of the dentition; dentoalveolar volume; root morphology; possible supernumerary, impacted or ankylosed teeth and other dental abnormalities; temporomandibular joints; airways; and skeletal structures is necessary to understand completely the cause of the malocclusion, diagnosis, treatment planning and specific biomechanical therapy in the management of the patient’s condition.

CONCLUSIONS

CBCT offers advantages for imaging in orthodontics. As a result, CBCT is being adopted in many dental practices. The clinical value proposition of CBCT is that it can describe craniofacial anatomy accurately and provide comprehensive information regarding anatomical relationships and individual patient findings for improved diagnosis, treatment planning and prognostication. Research and development of future applications of CBCT, such as simulation, growth prediction, forensics, modeling and manufacturing, is ongoing.

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