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Cone beam computed tomography use in orthodontics

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ABSTRACT

Cone beam computed tomography (CBCT) is widely used by orthodontists to obtain three-dimensional (3-D) images of their patients. This is of value as malocclusion results from discrepancies in three planes of space. This review tracks the use of CBCT in orthodontics, from its validation as an accurate and reliable tool, to its use in diagnosing and treatment planning, and in assessing treatment outcomes in orthodontics.

Keywords: Cone beam computed tomography, imaging, orthodontics, radiography.

Abbreviations and acronyms: CBCT = cone beam computed tomography; CL/P = cleft lip/palate; EARR = external apical root resorption; TADS = temporary anchorage devices.

INTRODUCTION

Malocclusion is a three-dimensional problem resulting from vertical, transverse and anterior-posterior discrepancies in the teeth, maxilla and/or mandible. It comes as little surprise that orthodontists immediately welcomed the 3-D rendering capacity of cone beam computed tomography (CBCT) as a means to optimize diagnosis and treatment planning malocclusion. Indeed, each new graduating class of orthodontics residents is gaining significant didactic and hands-on experience in CBCT imaging in orthodontics.[1] Moreover, research on CBCT use in diagnosis, treatment planning and treatment outcomes has confirmed its promise as an indispensible tool in orthodontics. This review will cover CBCT use in orthodontics and the exciting directions the technology is heading in.

SCOPE OF THE REVIEW

Publications for this review were initially obtained through a search of the PubMed database using keywords related to cone beam and orthodontics. Only articles in English were reviewed. Additional publications were identified through references in the initial list of articles. Related publications were grouped together and summarized to provide the reader with an overview of CBCT use in orthodontics diagnosis, treatment planning and outcomes measures.

CBCT accuracy and reliability – cephalometrics

As with all emerging technologies, CBCT first had to be put through its paces to prove its value. In orthodontics, this meant clinicians had to reliably and accurately identify anatomic landmarks and measure distances between those landmarks on CBCT-generated images. Failure to accomplish this would make the technology useless in orthodontics as these measurements are utilized to diagnose and treatment plan malocclusion and assess treatment outcomes. Thus, significant effort has been devoted to comparing diagnostic and outcomes measurements taken from CBCT images against measurements taken from conventional 2-D radiographs. There is widespread agreement that CBCT images are better than conventional 2-D lateral cephalographs,[2–10] posterior-anterior cephalographs[11] and panoramic radiographs[12] for landmark identification and measurement accuracy. Only three studies did not validate CBCT image superiority over 2-D lateral cephalograph.[10,13,14] Even in a rigorous test against the gold standard of caliper measurements on dry skulls, CBCT measurements were deemed clinically accurate, although the mean percent measurement error for CBCT images was 2.31% compared to 0.63% for calipers.[15] CBCT overcomes the sources of error in conventional 2-D radiographs: relatively low resolution, magnification error, image distortion and superimposition of structures.[16]

Regardless of the imaging modality, accuracy and reliability in landmark placement and measurements rely upon the image resolution. Orthodontists typically utilize a 12" sensor to capture the craniofacial region, although smaller sensors are sometimes utilized, especially for imaging impacted teeth. Only a limited number of studies have compared large vs. smaller sensors or CBCT units with high vs. low resolution and their effectiveness in orthodontics diagnosis and treatment planning. No differences in measurement accuracy were noted between a dry skull imaged with a 12" and 9" sensor.[17] Likewise, a comparison of 3-D surface rendering accuracy at 0.40 mm vs. 0.25 mm voxels showed no difference in measurement accuracy between the two resolutions.[18]

Emerging from CBCT and conventional 2-D image comparison studies is an important caveat for clinicians and researchers. Because of measurement error and magnification differences between CBCT and 2-D images, assessing growth or treatment outcomes in patients with 2-D initial radiographs and progress or final CBCT radiographs is strongly discouraged.[8,9,13,19] An algorithm to address the magnification error in 2-D images has been generated,[19] but landmark placement and measurement error still remain as potential sources of inconsistency that can adversely effect study conclusions.

CBCT accuracy and reliability – dental arch analysis

With clinical offices transitioning from hard copy to digital records, orthodontists are beginning to use digital casts for diagnosis and treatment planning. There are currently two approaches to generating digital casts that involve CBCT. The first uses CBCT to scan impressions of the patient's teeth to generate a digital model. The second bypasses the impressions and uses CBCT of the patient's teeth. Only a limited number of studies have evaluated these approaches, so evidence-based clinical guidelines for using this technology for diagnosis and treatment planning are not yet available, although a preliminary study showed that a medium field (9") sensor with the patient in an open-mouth position and an image with an anisotropic voxel size of 0.4 x 0.6 mm produces the optimal CBCT image of the dental arches.[20] CBCT scans of alginate and vinylpolysiloxane impressions of a typodont are both accurate for measuring intra-arch parameters (arch perimeter, arch width), but not interarch occlusal relationships.[21] Overbite, overjet, intercanine width, intermolar width and arch length discrepancy measurements from CBCT images of dried skulls are slightly smaller than the same measurements made directly on the skulls with calipers.[22] However, Little's irregularity index, overbite and overjet measurements from CBCT scans were as accurate as digitized dental impressions of patients.[23] With continued improvements in the technology, there is little doubt that digital models will become the standard in orthodontics practices.

CBCT image analysis

While orthodontists broadly accept the measurement accuracy of CBCT cephalographic images, the question of what measurements to use for diagnosis arose early in CBCT use. The conventional 2-D lateral cephalograph and numerous cephalometric analyses have been used for decades to diagnose malocclusion. Age-, gender- and ethnicity-specific norms for linear and angular craniofacial measurements exist for these analyses, but none exists for CBCT images. Thus, early adopters of CBCT imaging in orthodontics usually generated lateral cephalographs from the CBCT images and utilized conventional cephalometric analyses to make their diagnoses and superimposed the images to assess growth and treatment outcomes. This, of course, negated the benefit of CBCT's 3-D imaging power. Recent innovations in 3-D superimposition software programmes permit accurate cephalometric measurements.[24–27] These programmes utilize algorithms that optimally align images and colourize the regions where treatment effects are measureable. Importantly, data from the outcomes studies will guide identification and standardization of clinically relevant cephalometric landmarks. This is currently a problem as CBCT measurements are less accurate in the coronal plane than the sagittal or axial planes, in part, because coronal CBCT landmarks are poorly defined.[7]

Orthodontic diagnosis and treatment planning

CBCT's strength lies in its ability to image craniofacial anatomy in three dimensions. For orthodontists this translates into improved visualization of tooth position, skeletal features, airway patency and facial soft tissue. This, in turn, improves orthodontic diagnosis and treatment planning. Equally important are treatment outcomes studies which look at these same features to determine if the expected results for any given treatment were obtained.

Tooth localization

Impacted and ectopic teeth, especially canines, are very common problems in orthodontics patients.[28] Conventional 2-D radiographs – periapicals, occlusals, panoramics – are sufficient to identify an impacted tooth and, using the SLOB rule (same lingual, opposite buccal), to localize the tooth to one side of the alveolus or the other. CBCT not only provides this information, but it also shows the proximity of the impacted tooth to adjacent roots.[29–33] This is critical information for determining the biomechanics treatment plan needed to bring the impacted tooth into the arch without damaging adjacent teeth. Given the clarity of the images and precise localization of an impacted canine and adjacent structures in CBCT images, it is not surprising that clinicians report greater confidence in their diagnosis and treatment planning for impacted canines when they have CBCT images of the patient.[30]

External apical root resorption

Failure to direct impacted canine eruption forces properly can result in external apical root resorption (EARR) of the adjacent teeth. Moreover, routine orthodontic tooth movement causes irreversible EARR.[34] Precisely quantifying EARR could not be done prior to CBCT imaging because of distortion and magnification on 2-D radiographs.[33] Anatomic structures and their CBCT images are in a 1:1 ratio,[17] which makes accurate measurements of small changes in dental or skeletal anatomy possible. In fact, root length measurements from CBCT images are within 0.05 mm of their actual length[35] and *in vivo* tooth volume is within –4 to 7% of actual tooth volumes.[36] Overall, root lengths measured from CBCT images are more accurate than those taken from 2-D images.[12,33,35,37–40]

EARR studies not only provide valuable clinical information, but several of these studies have tested the accuracy and reliability of measurements taken on different CBCT machines and at different image resolutions, which can vary considerably[33,38,41] or at different voxel sizes.[37,39] Image resolution can be quite different between CBCT machines depending on the sensor used, with relatively low-resolution, large-volume images being generated on 12'' sensors (e.g. NewTom units) and relatively high-resolution, small-volume images being generated on 6'' sensors (e.g. 3D Accuitomo units). Not surprisingly, the latter images are especially good for measuring small changes in root length.[33,38] In all cases, CBCT images with voxel sizes ranging from 0.2 to 0.4 mm^3 are better than conventional 2-D radiographs for measuring root length.[37,39]

Temporary anchorage devices and palatal and alveolar bone thickness

Bone-borne point of force application through temporary anchorage devices (TADs) or mini-screws has revolutionized how orthodontists move teeth. TADs eliminate the frustration of unwanted tooth movement and give orthodontists much greater control over the movement of single teeth or groups of teeth than previously possible.[42] One technical issue with TADs is the tendency for approximately 15% of them to loosen within 12 weeks of placement,[43] which requires placing a new TAD, in a different position, and replanning the mechanics for the patient. In addition to the physical features of the TAD (length, tapered vs. non-tapered, single vs. double thread, interthread distance, material and coating), possible contributors to TAD failure are the bone quantity and quality into which the TAD is placed.

The majority of TADs are placed into the palate or into the maxillary or mandibular buccal alveolar bone. CBCT images offer an ideal means to visualize the bone thickness at the proposed TAD placement site for each patient. The thickest portion of the palate is 4 mm posterior to the incisive foramen and 3–6 mm lateral to the midpalatal suture, with gradual thinning posteriorly and laterally from this site.[44–49] Alveolar buccal bone is thicker in the mandible than the maxilla and thickness in the mandible increases with increasing apical distance from the alveolar crest.[48,50] Although no studies have yet been published on the effect of bone density on TAD stability in orthodontics patients, there is convincing evidence that high bone density – as measured by CBCT – increases dental implant stability.[51]

One risk of TAD placement in orthodontics patients is PDL contact or root contact, which occurs in 65.2% of cases.[42] To avoid root damage from TADs, root location and interradicular spacing must be measured prior to TAD placement. CBCT images are ideal for this task. Interradicular spacing in the maxilla is between 1.6 to 3.5 mm and 2.0 to 5.2 mm in the mandible.[42,48] The small interradicular space has led some authors to recommend using a guide stent when placing TADs into dentate alveolar bone.[50,52,53]

Rapid palatal expansion and alveolar bone thickness

Alveolar bone thickness is also of interest to orthodontists who use rapid palatal expansion to increase the transverse dimension of the maxilla. Most rapid palatal expanders are tooth-bone and produce varying degrees of skeletal expansion and dental tipping, depending upon the age of the patient at the time of treatment. Younger patients with a patent midpalatal suture have greater skeletal expansion than older patients in whom the suture has fused.[54,55] As a result, older patients have greater dental tipping during rapid palatal expansion and the concern is the effect this has on the supporting alveolar bone. Again, CBCT images provide an invaluable resource for assessing this effect.[35,56] While all studies on rapid palatal expansion treatment demonstrated both dental and alveolar tipping, none found detrimental effects (such as dehiscences or fenestrations) to the alveolar bone supporting the posterior teeth.[57–63] CBCT images are clear enough to measure alveolar bone thickness to an accuracy of 0.6 mm.[64,65] In fact, one recent study suggested that CBCT images with a voxel size of 0.4 mm actually overestimate alveolar bone loss following rapid palatal expansion.[66]

Cleft lip/palate patients

There is probably no patient population for whom CBCT is more critical than those with craniofacial anomalies.[2] Since cleft lip/palate (CL/P) is the most common craniofacial anomaly,[67] it is not surprising that research on CBCT imaging in craniofacial anomalies has focused on these patients. Following early clinical cases demonstrating the efficacy of CBCT use in CL/P patients,[68,69] including one study proposing 18 new cephalometric measurements specifically for CBCT images of CL/P patients,[70] researchers examined the alveolar cleft volume to help with pre-alveolar graft surgery.[71–73] In patients with unilateral CL/P, the average cleft volume was calculated to be 0.61 cm^3, while in bilateral CL/P the combined average cleft volume was 0.82 cm^3.[71] These data are important because they give surgeons a means of determining the amount of graft material needed to reconstruct the alveolus.[74] In addition, one study shows that canines on both the cleft and non-cleft side erupt incisally, facially and mesially, with only 12% on cleft-side canines requiring surgical exposure.[74] Together with the CBCT volumetric analyses, this information can guide the surgical placement of the proper amount of graft material to ensure sufficient alveolar bone to support canine eruption in CL/P patients.

In addition to imaging the alveolar cleft in CL/P patients, CBCT is also used to examine their soft tissues. Radiographs, whether conventional or CBCT, are primarily used to assess mineralized tissues. In CL/P patients, the soft tissue profile follows the underlying maxillary skeletal and dental anomalies. CBCT was used to demonstrate nasal and labial differences between age-matched non-CL/P patients, CL/P patients without synchronous rhinoplasty and CL/P patients with synchronous rhinoplasty.[75] Synchronous rhinoplasty is nasal reconstruction performed at the time of primary lip repair. Based upon differences in soft tissue measurements from CBCT images between the three groups, it is recommended that CL/P patients receive synchronous rhinoplasty to optimize nasal and labial appearance.

Airway patency

Although altering the airway is not an objective of orthodontic treatment, airway imaging is unavoidable on lateral cephalographs and large field of view CBCT commonly used in orthodontics. As a result, narrow airways are readily observed and patient referrals for adenoidectomy/tonsillectomy or obstructive sleep apnoea therapy can be made when needed. An advantage of CBCT imaging over conventional 2-D imaging is the ability to measure volumes, which provides an added dimension to assessing airway patency. Beyond the generic diagnosis of ‘narrow airway’, CBCT volumetric measurements permit a patient’s airway to be mapped with areas of constriction noted with precision.[76–80] This ability of CBCT to capture airway volumes has not escaped the notice of orthodontists who have looked for changes in airway volumes following rapid palatal expansion[81] and premolar extraction.[82] In both cases, airways remained unchanged following treatment.

Incidental findings

Standard of care requires that clinicians examine all radiographic images for pathology[83] and CBCT generates highly detailed images capable of localizing unsuspected pathology. The orthodontics literature has several case reports demonstrating this.[84–86] In fact, CBCT is in such widespread use that rates of incidental findings on CBCT images taken of orthodontics patients are now being published. The overall rate of incidental findings on CBCT images is 24.6%, with airway (21.4%), TMJ (5.6%) and endodontic (2.3%) pathology ranking among the most common in orthodontics patients.[87] In a separate study, unexpected maxillary sinus pathology appeared on 46.8% of CBCT images of orthodontics patients.[88]

Value of CBCT in orthodontics

There is little debate that CBCT provides highly detailed radiographic images suitable for diagnosis and treatment planning in orthodontics. Debate arises when considering the need for CBCT, rather than conventional 2-D, imaging. A lateral cephalograph or panoramic radiograph does not require as much radiation as a CBCT scan[89,90] and often provides sufficient data to make an accurate diagnosis and treatment plan. Some authors suggest that CBCT should be utilized infrequently and only in cases where conventional 2-D imaging will clearly not suffice.[12,49,91] The British Orthodontic Society (BOS) has updated its guidelines for clinical radiology to emphasize the invasiveness of any radiograph and the need for sound clinical judgment when prescribing diagnostic radiographs.[92] Importantly, the BOS guidelines make it clear that there are no criteria for taking routine radiographs, including CBCT scans, in orthodontics patients. At the time of this writing, no position paper detailing absolute and relative indications for CBCT imaging in orthodontics patients in the US is available, although the American Association of Orthodontists (AAO) House of Delegates, AAO representatives and the American Association of Maxillofacial Radiology are preparing new guidelines for radiology in orthodontics.[93]

Future applications of CBCT in orthodontics

As we look to the future of CBCT use in orthodontics there is a significant trend toward improved treatment planning and outcomes prediction incorporating CBCT images into 3-D modelling and finite element analysis.[94–97] This approach predicts stress distributions on the maxilla or mandible, teeth and orthodontic appliances during treatment, e.g. during rapid palatal expansion[96] or extraction space closure using TADs.[95] The goal of this research is to determine how the patient's craniofacial skeletal features will respond to various appliance designs, to generate patient-specific approaches to orthodontic treatment. This approach relies on integrating much of the published research on CBCT imaging in orthodontics. For example, this approach can determine where palatal or buccal bone is optimal for TAD placement and how much force will allow for tooth movement with minimal EARR. Regardless of where the future takes us, the literature on CBCT imaging in orthodontics provides a remarkable database for designing applications to improve diagnosis, treatment planning and outcomes assessment in orthodontics.

SUMMARY AND CLINICAL SIGNIFICANCE

CBCT is a powerful imaging modality that provides orthodontists with 3-D images of their patients' craniofacial skeleton, dentition and soft tissue, all of which vary from ideal when malocclusion is diagnosed. With continued advancements in software development to manipulate CBCT images, the diagnostic and treatment planning value of these images will rise considerably in the near future. While orthodontists await the American Association of Orthodontists' position paper on identifying appropriate cases for CBCT imaging, case selection using current evidence-based criteria suggest that complex craniofacial and surgical cases and cases of missing or impacted teeth may be the most suitable candidates for CBCT imaging, although the absolute need for CBCT imaging must be determined on a case-by-case basis. Overall, CBCT imaging provides orthodontists with an excellent tool to improve diagnosis, treatment planning and outcomes assessment in appropriate malocclusion cases.

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