REVIEW

The current status of cone beam computed tomography imaging in orthodontics

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Cone beam CT (CBCT) has become an increasingly important source of three dimensional (3D) volumetric data in clinical orthodontics since its introduction into dentistry in 1998. The purpose of this manuscript is to highlight the current understanding of, and evidence for, the clinical use of CBCT in orthodontics, and to review the findings to answer clinically relevant questions. Currently available information from studies using CBCT can be organized into five broad categories: 1, the assessment of CBCT technology; 2, its use in craniofacial morphometric analyses; 3, incidental and missed findings; 4, analysis of treatment outcomes; and 5, efficacy of CBCT in diagnosis and treatment planning. The findings in these topical areas are summarized, followed by current indications and protocols for the use of CBCT in specific cases. Despite the increasing popularity of CBCT in orthodontics, and its advantages over routine radiography in specific cases, the effects of information derived from these images in altering diagnosis and treatment decisions has not been demonstrated in several types of cases. It has therefore been recommended that CBCT be used in select cases in which conventional radiography cannot supply satisfactory diagnostic information; these include cleft palate patients, assessment of unerupted tooth position, supernumerary teeth, identification of root resorption and for planning orthognathic surgery. The need to image other types of cases should be made on a case-by-case basis following an assessment of benefits vs risks of scanning in these situations.

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Introduction

The goal of diagnosis and treatment planning of individuals requiring orthodontic treatment is to plan a course of treatment based on the patient's chief complaint, the initial condition of the patient's problem/s, the achievable treatment goals and the patient's willingness to accept and co-operate with a specific treatment protocol. Accurate diagnostic imaging is an essential requirement to derive the correct diagnosis and optimal treatment plan, as well as monitor and document the treatment progress and final outcome.¹

Two-dimensional (2D) diagnostic imaging, including traditional radiographs, cephalometric tracings,

photographs and video imaging, has been a part of the orthodontic patient record for decades. The limitations in analysis of these imaging modalities are well known, and 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.^{2,3} In contrast, three-dimensional (3D) imaging allows for the evaluation and analysis of "the anatomical truth".^{4–6} Until recently, 3D information has been confined to plaster and even more recently digital study models, as well as the clinical examination of the patient. Over the past decade, cone beam CT (CBCT) has increasingly become an important source of 3D volumetric data in clinical orthodontics. Traditionally, the information derived from all these sources has not been co-registered into an accurate 3D representation

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of the patient's anatomy to create a "virtual patient". To make the transition to a more commonly accepted and reliable use of 3D imaging technologies in orthodontic clinical practice, these technologies need to be further developed and their efficacy in enhancing diagnosis and treatment planning in specific situations needs to be verified.

Despite the increasing popularity of CBCT, opinion on the overall use of CBCT in orthodontics ranges from advocating its routine use for all orthodontic patients, by some clinicians in private practice and at a small number of academic institutions, to guidelines on its limited use in specific cases.⁷ The latter guidelines recommend the use of CBCT in select cases in which conventional radiography cannot supply satisfactory diagnostic information. These cases include cleft palate patients, assessment of unerupted tooth position, identification of root resorption caused by unerupted teeth and planning orthognathic surgery.⁷ Furthermore, the American Association of Orthodontists recently adopted a resolution stating that while the organization recognizes "that there may be clinical situations where a CBCT radiograph may be of value, the use of such technology is not routinely required for orthodontic radiography" (American Association of Orthodontists Resolution 26–10H, 2010). This sentiment is supported by the current status of scientific evidence cited in this manuscript that recommends CBCT imaging of specific cases where its use has been substantiated to enhance diagnosis and treatment planning and in which its benefits exceed the risks.

Although anecdotal observations, published case reports on topics ranging from impacted teeth to temporomandibular joint (TMJ) morphology, and treatment outcomes suggest that important information is obtained through CBCT imaging, scientific evidence that the use of CBCT alters diagnosis and improves treatment plans or outcomes has yet to be established for many of its purported applications. In areas where the use of CBCT is logical, supported by scientific evidence or both, the specific indications for acquiring CBCT images and protocols to be used for imaging and extracting appropriate information have not been fully resolved. Finally, the information obtained from CBCT imaging requires a substantial level of expertise for interpretation. This implies that the untrained clinician is likely to have a substantial error rate in the interpretation of CBCT images resulting in a high percentage of missed or false-positive diagnoses.⁸

The purpose of this review is to highlight the current understanding of, and the evidence available for, the clinical use of CBCT in orthodontics, and review the findings to answer clinically relevant questions. More specifically, this review provides insights into currently available information from studies using CBCT organized into five broad categories, namely 1, the assessment of the technology, including measurement of accuracy, radiation exposure and comparisons with

spiral CTs; 2, CBCT's use in craniofacial and airway morphometric analyses in health and disease; 3, incidental findings, missed findings and medico-legal implications when using CBCT; 4, CBCT's use in analyzing treatment outcomes; and 5, use and efficacy of CBCT in diagnosis and treatment planning. Findings in these topical areas are outlined below, followed by current indications and protocols for the use of CBCT in specific cases.

Current scientific status of the use of CBCT

Technology assessment

Radiation exposure and comparisons between CBCT and other forms of imaging: CBCT has substantially lower radiation, but lower resolution than spiral CT.⁹ The currently available CBCT units have variable radiation exposure in the range of 87 to 206 μ Sv for a full craniofacial scan.^{10,11} Thus, when compared with the combined radiation exposure of conventional orthodontic images including a panoramic radiograph (14.2–24.3 μ Sv), a lateral cephalogram (10.4 μ S) and a full-mouth series (13–100 μ S), CBCT radiation exposure is equivalent to or slightly higher than traditional imaging.¹⁰

Accuracy of CBCT-derived cephalograms and measurements vs gold standard: Cephalograms reconstructed from CBCT data have no statistically significant difference in linear and angular measurements relative to traditional cephalograms,^{9,12} whereas measurement error from CBCT images are lower than those from cephalograms.³ 3D measurements from CBCTs can be made in several visualization modes, including multiplanar (MPR), volume rendered (VR) and shaded surface display (SSD).^{13,14} Of these, point-to-point measurements made in the MPR mode are highly accurate when compared with physical skull measurements, whereas the surface anatomy measured in VR and SSD modes have a measurement error of 2.3% as compared with direct physical measurements.^{14,15} The error in VR and SSD display modes results are due to the fact that the surface contours are estimated in these modes. These findings suggest that identification and targeting of landmarks should be done using the digital imaging and communications in medicine (DICOM) volume in an MPR display mode.

Comparison of CBCT vs panoramic radiography: A subjective comparison of images from two CBCT units (NewTom 9000, QR s.r.l., Verona, Italy and Arcadis Orbic 3D, Siemens Medical Solutions, Erlangen, Germany) and routine panoramic radiography demonstrated that CBCT provides more information than the radiographs for localizing impacted and retained teeth, root resorption, cleft lip and palate (CLP), and third molar evaluations but not for changes in the TMJ.¹⁶

Use of CBCT in morphometric analysis in health and disease

Root morphology and resorption: Root length, root form and root resorption have traditionally been assessed *via* periapical radiographs. However, CBCT could provide enhanced visualization of roots, making it a valuable tool for assessing pre-orthodontic or post-orthodontic root resorption. The mean difference between direct and radiographic CBCT measurements of root length has been shown to be 0.05 mm (SD $\pm$ 0.75).¹⁷ Although these differences were statistically significant for some teeth, the statistical analysis appears not to have corrected for multiple comparisons performed in the study that would have diminished the number of significant differences found. Also, determination of measurement error of *in vivo* root lengths showed an error of approximately 0.2 mm in the pre- and post-treatment measurements.¹⁷ Although these findings show some value in the use of CBCT in determining root resorption and morphology, additional studies assessing the efficacy and sensitivity of CBCT in detecting root resorption and evaluating root morphology are recommended.

Dental and root spatial relationships and dentoalveolar morphometrics: When using a typodont with ideally positioned teeth, CBCT has been shown to be better than orthopantomograms in determining root angulations, but still shows variations from the true anatomy.¹⁸ In contrast, CBCT is at least as good as periapical radiography for assessing root and tooth length.¹⁹ Finally, CBCT provides accurate assessment of alveolar bone height assessment, but because CBCT had a high number of false-positives in the determination of fenestrations, caution must be used regarding evaluating these defects on CBCT images.^{17,20}

Craniofacial morphometrics: 3D imaging can allow for analysis of the size, shape and volumetric differences in bilateral structures as well as growth changes in 3D.¹⁴ This is likely to offer refined and quantifiable diagnoses in all three planes of space that may be clinically significant enough to alter treatment planning decisions. These types of evaluations are likely to offer new information on growth of the craniofacial region in 3D, including assessment on how the head of the condyle develops mediolaterally and the mandible broadens. Additionally, CBCT scans enable clinicians to mirror the normal side onto the discrepant side to simulate and visualize the desired end result and plan surgery to facilitate correction.²¹

Bone quality and quantity assessments: With the widespread use of temporary anchorage devices (TADs), the determination of bone volume, bone quality, and the location of adjacent structures have become important in providing orthodontic treatment. It has been shown that a location 4 mm palatal to the incisive

foramen provides excellent bone volume for palatal bone screws.^{22,23} A technique using high-resolution CBCT scans and rapid prototyping to fabricate surgical guides has also been described for placing TADs on the buccal aspect of the jaws.²⁴

TMJ anatomy in health and disease: Little information is currently available on the efficacy of CBCT scans in enhancing the diagnosis of TMJ disorders over routine radiography. It has, however, been reported that little additional information on gross morphological changes in TMJ structures is derived from CBCT relative to an orthopantomogram in the majority of cases (86%).¹⁶ In contrast, in a more refined study, interactive and static CBCT scans demonstrated cortical erosions more accurately (95% and 77%, respectively) than normal panoramic projections (65%), thereby providing more diagnostic accuracy for detailed assessment of the articular surface of the TMJ.²⁵ Also, using shape correspondence methods, significant differences between the morphologies of healthy and degenerative condyles have been demonstrated, and a significant correlation of both pain intensity and duration with changes in 3D morphology of the osteoarthritic condyles have been found.²⁶

Airway morphology and relationship to obstructive sleep apnea: While outside the scope of this manuscript, recent publications have demonstrated the ability of CBCT to accurately image the airway to provide minimum cross section and total airway volume in obstructive sleep apnea (OSA) patients and controls.²⁷ However, at this time no studies have demonstrated that CBCT images accurately predict OSA.

Incidental findings, missed findings and medico-legal implications

The incidence of incidental findings in CBCT images unrelated to the original purpose of the scan have been reported to be as high as 25% in a group of 500 consecutively scanned individuals.²⁸ These included airway findings, TMJ abnormalities and endodontic lesions. An additional question that requires further study is the capability of the orthodontist to identify non-orthodontically relevant findings and to make appropriate referrals when needed. Lack of the recognition of incidental lesions can have substantial medico-legal ramifications. In contrast, the potential for inadvertent diagnosis of false-positive findings by the untrained eye have the potential to add unnecessary costs to healthcare, as well as cause unnecessary anxiety to the patient and family. In a recent study, it was shown that orthodontists and orthodontic residents miss approximately 67% of lesions and have a 50% false-positive detection rate in CBCT images.⁸ Following a 3 h training session by an oral maxillofacial radiologist, the error rate in these two measures dropped to 33% and 30%, respectively. This error rate is relatively high compared with historical

gold standard data on lesion detection by trained radiology specialists. These findings suggest that CBCT taken for orthodontic purposes should be read by an oral maxillofacial radiologist and that increased training in viewing normal and abnormal anatomy in CBCT images would provide an additional valuable mechanism for orthodontists to further identify important components relevant to their diagnosis.

Use of CBCT in assessing treatment outcomes

Maxillary expansion: Studies using CBCT on rapid maxillary expansion treated cases have revealed that although the total overall expansion that includes dental tipping, alveolar bone bending and skeletal expansion at the first premolar, second premolar and first molar were of similar magnitude, the skeletal expansion was greater in the anterior than posterior maxilla.^{29,30} In addition, buccal crown tipping was accompanied by a decrease in buccal bone thickness and buccal marginal bone height.³⁰ Of the total expansion obtained in this sample from one study: 38% was orthopaedic; 13% was due to alveolar bending; and 49% resulted from dental tipping.²⁹ It is therefore likely that most post-expansion relapse occurs owing to rebound from alveolar bending and dental tipping because these two modalities of expansion are hard to retain. Additionally, the sample showed an increase in nasal width and decrease in maxillary sinus width.

Quantifying CLP defects and outcomes of alveolar bone grafts: A comparison of CBCT with panoramic radiographs to determine the success of alveolar bone grafts in patients with CLP has shown that although the panoramic radiograph enables clinicians to approximate the vertical bone height of the bone bridge, they do not permit clinicians to determine the buccal-palatal width of the bone.³¹ In addition, the CBCT image enables the visualization of the 3D morphology of the bone bridge, the relationship between the bone bridge and roots of neighbouring teeth and their periodontal condition. All of this information is important in the decision-making process for implant placement. A subsequent study that compared patients before and after cleft grafting demonstrated an 84% bone fill of the cleft defect 1 year after the graft was placed.³²

Orthognathic surgery: Studies on surgical treatment outcomes may be facilitated by using a new superimposition method that enables the operator to superimpose a custom surface mesh of the first CBCT image onto the second CBCT on the anterior cranial base.^{26,33} This enables qualitative and quantitative comparisons using a colour map that can be rotated in all planes of space to document the changes resulting from surgery. By using colour spectrums that indicate the amount and direction of change, this method of superimposition may become a valuable tool in assessing 3D changes in bone and soft-tissue facial structures with growth, treatment or both.

Use of CBCT in orthodontic diagnosis and treatment planning

Although CBCT imaging clearly enhances the visualization of normal and abnormal anatomy and pathologies, the impact of the additional information obtained from these scans in refining or changing treatment plans in various situations is less clear. Of the topics discussed, impacted canines is the one in which CBCT has been shown to improve diagnosis and possibly contribute to modifications in treatment planning. CBCT has been shown to enhance the ability to accurately localize the canine, evaluate its proximity to other teeth, examine the follicle size and assess resorption of the adjacent teeth.³⁴ A recent study compared variations in the diagnostic information derived from routine 2D radiographs that included panoramic, occlusal and two periapical views with 3D CBCT images and subsequent effects of this information on the treatment decisions by orthodontists.³⁵ The orthodontists had substantially different perception of localization and root damage, and a significantly higher confidence in diagnosis and treatment planning with CBCT images than with routine radiographs. More importantly, the original treatment plans derived from the 2D radiographs were modified for more than a quarter of the teeth when the orthodontists viewed the CBCT images. This study clearly demonstrates the use of CBCT in both refining diagnosis and modifications in treatment plans of a significant number of impacted teeth, thus validating the use of this imaging modality for impacted teeth.

Clinical protocols and uses

Imaging goals and protocols

CBCT imaging goals in orthodontics should include detection of anatomical features as well as morphological measurements of size and of anatomical relationships. Anatomical features include orthodontic landmarks and descriptors of anatomy that help to differentiate between normal and abnormal anatomy. Ideally, CBCT imaging protocols should take into consideration the relative advantages of this technology over routine radiography, including the quality of the information derived, its potential impact on diagnosis and treatment planning, the ease of use *vs* the risks (including radiation exposure) and financial costs. This subjective benefit-to-risk assessment may be termed “value proposition” for taking CBCT scans for any given case.

An imaging protocol for orthodontic purposes should take several factors into consideration. The image should incorporate the desired field of view (FOV), which in turn is determined by the region of interest. The provider must decide what the image he or she is taking is trying to accomplish for the patient. The FOV may be small (individual teeth or quadrant), medium (both arches including TMJ) or large (full head). The smaller FOV is used for assessing individual teeth, for example impacted teeth, root morphology,

supernumeraries, etc. or sites for placement of dental implants or TADs. Medium FOV includes the mandible, the maxilla or both, and would typically be used when additional information on occlusal relationships, facial asymmetries or bilateral TMJ evaluations is needed or when the condition/s of interest, such as potentially adverse boundary conditions, are present in both arches or jaws. The largest FOV includes the whole head and helps clinicians to visualize relationships between skeletal bases, between teeth and skeletal bases as well as significant anomalies in patients requiring orthognathic surgery or those with craniofacial anomalies. For maximum quality and diagnostic value the images should be obtained with maximum detail, minimal distortion and minimal superimposition. After imaging, the clinician should view the region of interest from at least two planes at right angles to each other, which will offer a multidimensional perspective. The clinician should also view the volumetric rendering in a

3D format. Additionally the clinician should scan through consecutive series of 2D views in any given plane over the entire region of interest.

Case selection and use of information derived

While there is currently limited information available to justify the use of CBCT in routine orthodontic cases, on the basis of a benefit-to-risk assessment that results in a positive “value proposition,” several types of cases may benefit from additional information obtained from CBCT.⁷ The potential outcomes of the additional information derived from 3D CBCT images over traditional 2D radiographs may range from a refinement or substantiation of certain types of treatment to a total change in the treatment plan. An amalgamation of the indications for CBCT from various sources suggests that the following types of cases could benefit from this imaging modality.

Figure 1 Rendered images from cone beam CT (CBCT) scans provide details in three dimensions for precise location of impacted canines and identifying associated root resorption as well as optimal planning for retrieving impacted teeth. (a) A panoramic radiograph provides limited information on the exact location of the canines and their relationship to the roots of the incisors. In contrast, (b) the occlusal, (c) frontal and (d) superior CBCT images of bilateral impacted canines show the presence of root resorption on both lateral incisors. These images also provide important information to the clinician on the best surgical approach, appropriate placement of the bonded attachments and planning of biomechanics. In this case the direction of movement of the canines should, initially, be distally away from the lateral incisor roots before moving these teeth into the arch. The left canine was more rotated and may require a different location for attachment placement compared with the right canine

Anomalies of teeth and roots: Impacted and transposed teeth are possibly the most common reason for use of CBCT imaging in orthodontics. The information derived can enhance the ability to localize impacted or transposed teeth, identify pathological conditions and

root resorption, help plan surgical access and bond placement, and define the optimal and most efficient path for extrusion into the oral cavity that avoids or minimizes collateral damage (Figures 1 and 2). Furthermore, CBCT scans can provide diagnostic information

Figure 2 Use of cone beam (CBCT) in diagnosis and treatment planning of transposed teeth. A case demonstrating transposed roots of the maxillary canines and first premolars in which CBCT reveals that the canine root is buccal to the premolar root. Evaluation of these (a) CBCT derived three-dimensional and (b,c) two-dimensional cross-sectional images may help the clinician to optimize treatment planning. This includes proactively moving tooth roots out of the path to be used and to relocate the transposed tooth or root, determining if the boundary conditions will permit such movement, planning the biomechanics (including the force systems, types and direction of movements), which together define the prognosis of moving transposed teeth or roots past each other

on roots of the adjacent teeth that are in close proximity to the impacted or transposed tooth or in its traction path that can be moved proactively and avoid causing damage. Another advantage of CBCT over routine radiographs includes the accurate measurement of the impacted tooth to aid in determining and developing the space needed for the tooth.

The presence of supernumerary teeth can pose a challenge to the clinician's ability to distinguish which tooth is actually the supernumerary and which one is the normal tooth. Accurate measurements and the determination of the precise location of the tooth from CBCT images allow the clinician to make an informed decision on which tooth, or teeth, to extract, the optimal surgical approach and help to minimize damage to the real tooth (Figure 3).

Relative to traditional radiographs, CBCT scans enable more sensitive and definitive diagnosis of root resorption associated or unassociated with impacted teeth (Figures 1 and 4). For root resorption resulting from impacted teeth, CBCT scans provide better visualization of roots than routine radiographs, which can have artefacts owing to superimposition of structures and the inability to observe the 3D root structure from all possible directions. The enhanced information derived

from CBCT scans compared with that from 2D images may be critical in changing treatment plans including, for example, the option to extract a resorbed lateral incisor over a premolar in an extraction case.

In addition to root resorption associated with impacted teeth, more generalized resorption of teeth including incisors may be overlooked with suboptimal periapical or panoramic radiographs. These findings in CBCT images may lead to modifications in treatment planning, such as avoiding extractions in borderline cases so as to reduce the duration of treatment and magnitude of tooth movement thereby mitigating additional root resorption.

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

Boundary conditions: The dentoalveolar anatomy establishes the boundary conditions during orthodontic tooth movement and also in the final positioning of teeth. For orthodontic treatment purposes, the boundary conditions may be defined as the amount (depth and height) and morphology of the alveolar bone relative to tooth root dimensions, angulation and spatial position. Boundary conditions may also complicate

Figure 3 Cone beam (CBCT) images offer important information for the finer details in treatment planning of supernumerary teeth. (a) The panoramic view shows the presence of a supernumerary tooth in the maxillary right lateral incisor area with delayed eruption of the maxillary right central incisor. It is difficult to discern from the panoramic view (or from periapical radiographs, not shown) which of the two teeth, marked with an asterisk and arrow head, would be morphologically optimal to serve as the lateral incisor. Since the contralateral lateral incisor has not yet erupted, it cannot be examined clinically for size and form for comparison. Various three-dimensional views from CBCT scans (b,c,d) allow the comparison of the two teeth in the maxillary right lateral incisor area with the unerupted upper left lateral incisor. An analysis of the mesiodistal measurements of these unerupted teeth revealed that the tooth marked with an asterisk most closely matches the morphology and dimensions of contralateral lateral incisor while the tooth marked with an arrowhead is almost 1 mm larger mesiodistally than the contralateral lateral incisor

Figure 4 The use of cone beam CT (CBCT) in the diagnosis of root morphology and boundary conditions. (a) Panoramic view of a patient with bimaxillary protrusion, which owing to its two-dimensional perspective, does not provide information on any potential buccolingual boundary limitations and suggests a near normal length of the roots of the maxillary anterior teeth (crown:root ratio of approximately 1:2). In contrast, the sagittal cross-sections along the long axis of the central incisors (b,d) as well as the three-dimensional reconstruction (c) show that the roots of the incisors are short (crown:root ratio of 1:1). Also, the boundary conditions particularly in the mandible where the labio-lingual width of the roots of the anterior teeth approximate the width of the cortical bone housing, would likely limit the clinician's ability to retract teeth. Despite orthodontic indications for extraction of four first premolars and high anchorage to retract maximally the incisors, the limits imposed by the short roots and boundary conditions resulted in a different treatment approach involving non-extraction treatment and a possible genioplasty at a later date

situations in which a transposed tooth needs to be moved back to its appropriate location (Figure 2). These anatomical boundary conditions may limit or dictate the planned or potential tooth movement as well as the final desired spatial position and angulation of the tooth (Figure 5). Root anatomy such as short or dilacerated roots may also determine the amount and direction that a tooth can be moved (Figure 4).

The visualization and characterization of these boundary conditions is best performed by carefully analyzing volumetric CBCT information during the initial workup. As with other types of cases, it is best to be selective about which cases may benefit from CBCT scans for assessing boundary conditions. These cases include patients with alveolar bone phenotypes that clinically appear too narrow to accommodate significant labiolingual or buccolingual displacements or angulations of teeth (Figures 4 and 5), patients with compromised periodontium or gingival anatomy or

both (Figures 5c,d) and patients in whom the movement of the tooth or teeth may entail translocation past another tooth or obstruction (Figure 2).

TMJ degeneration, progressive bite changes and functional shifts: Although they occur relatively infrequently, TMJ pathologies that result in alterations in the size, form, quality and spatial relationships of the osseous joint components often cause highly adverse clinical manifestations, progressive bite changes and lead to unpredictable orthodontic outcomes.^{36,37} When these conditions occur during mandibular development they can contribute to perturbed growth of the condyle of the affected joint, a decrease in ipsilateral mandibular growth and accompanying compensations in the maxilla, tooth position, occlusion and cranial base.^{36–38} Bilateral degenerative changes in the TMJ may alter the facial growth pattern, which can result in adverse skeletal and dental changes in the vertical,

Figure 5 CBCT provides novel information on boundary conditions that are not discernable from routine radiographs or during clinical examination, which may impact on treatment options. (a) Pre-treatment coronal view showing the lingual inclination (arrows) of maxillary premolars and proximity of their buccal roots of the to the cortical bone margin (arrowheads). (b) Post-treatment coronal view demonstrating that the limitations offered by the boundary conditions bone-root relationships have been addressed through lingual torquing of the roots such that the torque of these teeth more closely matches the inclination of the cortical and alveolar process of the maxilla. (c) Sagittal and (d) occlusal views from CBCT scans of an individual with severe limitations in boundary conditions where the cortical bone margins are incapable of sustaining orthodontic movements in any plane of space. Orthodontic treatment would be contraindicated in this case

horizontal and transverse directions. This can lead to mandibular retrusion, anterior open bite and Class II malocclusion (Figure 6). Changes attributed to both these types of events are difficult to characterize accurately with 2D radiographic imaging. In contrast, by allowing the concurrent visualization of TMJs, the maxillomandibular spatial relationships and occlusion, CBCT images provide clinicians with the opportunity to visualize and quantify the local and regional effects associated with TMJ abnormalities. Similarly, cases involving centric occlusion *vs* centric relation (CO/CR) discrepancies, unilateral Class II malocclusions or a retrognathic mandible may involve displacement of the position of the TMJ in CO *vs* CR, and could benefit from additional diagnostic information derived from CBCT scans.

Orthognathic surgery and distraction osteogenesis: CBCT imaging offers the ability to capture images and to analyze the craniofacial hard and soft tissues and their spatial relationships using virtual patient-specific models and appropriate software. Virtual anatomical models can be constructed from CT volume and co-registered with other available 3D image data. The virtual models can then be used to simulate or test treatment options, construct anatomically correct replacement grafts and ultimately be an important tool during the surgical procedure. Databases also can be linked to anatomical models to provide the modelled tissues with attributes that simulate tissue responses to growth, treatment and function. For example, facial soft tissues can be attributed with viscoelastic properties and linked to the underlying hard tissues so that simulated

Figure 6 Cone beam CT provides concurrent assessment of temporomandibular joint (TMJ) morphological changes and related discrepancies in craniofacial morphology as well as maxillomandibular and interarch dental relationships. (a) A patient with chronic degenerative TMJ disease of the right TMJ as well as (c) left condylar hyperplasia presents with an asymmetric Class II relationship. The height differences between the right and left condyles seen on the two dimensional cross-sectional views can be better related to each other and to maxillomandibular relationships on the three dimensional rendered view (b), which also demonstrates the asymmetric mandible and compensatory inclinations of the posterior and anterior mandibular teeth. This information may be important to the oral surgeon and orthodontist in planning, preparing for and performing orthognathic surgery

manipulation of the hard tissues (teeth and skeleton) produce an appropriate deformation response in the associated soft tissues. This process can provide a clearer representation of expected changes following treatment when compared with less sophisticated modelling.³⁹

Dental implants and temporary anchorage devices: CBCT imaging can provide valuable information for the placement of endosseous dental implants and TADs. The evaluation of the quantity and quality of bone from CBCT scans may help in identifying optimal implant sites for the implant or TAD, thereby enhancing the chances of success. CBCT scans can also provide useful visualization of neighbouring structures such as tooth roots, and can be valuable for avoiding damage.

Other facial phenotypes: Patients with other clinical conditions that may benefit from CBCT imaging include those with craniofacial anomalies, CLP, facial asymmetry, large anterior open bite and history of airway difficulties. The decision to obtain a CBCT in any of these types of clinical presentations should be determined on a case-by-case basis depending on

whether additional information may help modify diagnosis and the treatment plan.

Summary

In conclusion, over the past decade since the introduction of CBCT into dentistry several studies have accumulated valuable data on technology assessment, craniofacial morphology in health and disease, treatment outcomes and efficacy of CBCT images in diagnosis and treatment planning. Although CBCT continues to gain substantial popularity, its use is recommended primarily in select cases in which conventional radiography cannot supply satisfactory diagnostic information, including cleft palate patients, assessment of unerupted tooth position, supernumerary teeth, identification of root resorption caused by unerupted teeth, evaluating boundary conditions and planning orthognathic surgery. CBCT imaging of other types of cases in which it is likely to provide valuable diagnostic information can also be performed following determination of a positive value-proposition.

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