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CBCT in orthodontics: assessment of treatment outcomes and indications for its use

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Since its introduction into dentistry in 1998, CBCT has become increasingly utilized for orthodontic diagnosis, treatment planning and research. The utilization of CBCT for these purposes has been facilitated by the relative advantages of three-dimensional (3D) over two-dimensional radiography. Despite many suggested indications of CBCT, scientific evidence that its utilization improves diagnosis and treatment plans or outcomes has only recently begun to emerge for some of these applications. This article provides a comprehensive and current review of key studies on the applications of CBCT in orthodontic therapy and for research to decipher treatment outcomes and 3D craniofacial anatomy. The current diagnostic and treatment planning indications for CBCT include impacted teeth, cleft lip and palate and skeletal discrepancies requiring surgical intervention. The use of CBCT in these and other situations such as root resorption, supernumerary teeth, temporomandibular joint (TMJ) pathology, asymmetries and alveolar boundary conditions should be justified on the basis of the merits relative to risks of imaging. CBCT has also been used to assess 3D craniofacial anatomy in health and disease and of treatment outcomes including that of root morphology and angulation; alveolar boundary conditions; maxillary transverse dimensions and maxillary expansion; airway morphology, vertical malocclusion and obstructive sleep apnoea; TMJ morphology and pathology contributing to malocclusion; and temporary anchorage devices. Finally, this article utilizes findings of these studies and current voids in knowledge to provide ideas for future research that could be beneficial for further optimizing the use of CBCT in research and the clinical practice of orthodontics.

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Introduction

CBCT was introduced to dentistry in 1998¹ in Europe and approved for use in the USA in 2001.² An early assessment of the likely future impact of this technology to dentistry, and more specifically to orthodontics, was first discussed in a symposium on “Craniofacial Imaging in the 21st Century” held in 2002 in Pacific Grove, CA, and documented in its proceedings.³ Since then, CBCT technology has undergone a rapid evolution, driven largely by the demands of each speciality for accurate,

reproducible and safe three-dimensional (3D) images. In orthodontics, 3D imaging can help unravel the complexity of dental and skeletal malocclusions and improve diagnosis and treatment planning in specific case types.^{4,5}

The varied utilization of CBCT by clinicians for orthodontic purposes exists within the context of research evidence, published case reports or anecdotal observations on a broad spectrum of cases ranging from impacted teeth to temporomandibular joint (TMJ) morphology. Several of these studies show that CBCT provides clinically relevant information and novel 3D research data. Nevertheless, scientific evidence that the

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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 CBCT use is logical and/or supported by scientific evidence, the specific indications for acquiring CBCT images and protocols for imaging and extracting appropriate information have not been resolved fully. This article provides a review of literature on 3D craniofacial anatomy and orthodontic treatment outcomes determined by CBCT as well as evidence-based indications for the use of CBCT in clinical orthodontics. These include studies on impacted and supernumerary teeth, root resorption and angulations, cleft lip and palate (CL/P), alveolar boundary conditions, temporary anchorage devices (TADs), maxillary transverse deficiency, airway analyses, obstructive sleep apnoea (OSA), TMJ disorders and orthognathic and craniofacial surgery. 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, which will enable clinicians to realize the ultimate goal of increased treatment efficiency or outcomes or both in many more clinical scenarios than currently possible.

Radiology guidelines in orthodontics

Both European and US radiography guidelines specify that routine radiographs are not indicated for any patient in any dental discipline,^{6–10} including orthodontics,^{11,12} because the risk of unnecessary exposure to ionizing radiation may outweigh its benefits. In fact, three systematic reviews concur that two-dimensional (2D) and 3D radiographs are not routinely needed for diagnosis or treatment planning of orthodontic patients.^{13–15} Based on the radiography guidelines in the USA and Europe, it is now universally advised that a thorough clinical examination and adherence to the “as low as reasonably achievable” radiography principle should guide clinicians in their justification for and choice of radiographs needed to optimize diagnosis, treatment planning and outcomes assessment for their patients. It is even more critical to adhere to this principle when radiographing children who comprise the majority of orthodontic patients owing to the *attributable lifetime radiation risk*.^{16,17} When required, CBCT should be performed using the smallest possible field of view needed for the specific clinical scenario.⁵ Finally, the comparison of CBCT radiation exposure with the combined exposure of cephalograms and panoramic radiographs to justify the routine use of CBCT on orthodontic patients is based on a paradigm that assumes that all orthodontic patients should be subjected to routine 2D radiography. Indeed the findings of the systematic reviews^{13–15} suggest that these 2D radiographs should also only be taken when they are expected to provide additional information that could aid in

diagnosis or treatment planning or for assessing progress or complications during treatment.

Orthodontic research and findings using CBCT

A large proportion of published original CBCT studies have focused on craniofacial and airway morphometric analyses in health and disease; CBCT use in analysing treatment outcomes; and evidence-based indications, uses and efficacy of CBCT in diagnosis and treatment planning, that are summarised below.

Three-dimensional craniofacial morphometric analyses and superimpositions

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 alveolar boundary conditions as discussed below.

One of the key advantages of CBCT over 2D radiography is its ability to provide 3D volumetric, surface and sectional information about the craniofacial structures. This has enabled orthodontists and researchers in the field to overcome the substantial limitations of 2D radiographs, including magnification, geometric distortion, superimposed structures and inconsistent head position. In the earlier stages of incorporating CBCT for orthodontic purposes, there was a tendency to collapse the 3D data set to a 2D image since analyses of the images in this format were the only methods known to the profession for assessing relationships of the dental and skeletal structures.^{18,19} This is clearly not an optimal approach to utilizing and extracting all the information contained in the 3D data set. Since then, researchers have taken up the challenge of developing new software to measure 3D distances, angles and volumes and to superimpose 3D craniofacial images,^{20,21} although the development of software for these purposes lags behind that of the hardware.¹⁴

Currently, three main methods are used for analysing 3D craniofacial anatomy and changes due to treatment. The first method draws heavily from 2D cephalometric measurement methods to derive linear and angular measurements from 3D images.^{22–24} However, extracting 2D measurements from a 3D image results in loss of critical 3D information and diminishes the overall value of the 3D data set. The second method, called iterative closest point analysis determines the shortest distances between structures in two superimposed 3D images.^{25–29} These changes can then be represented as a colour map that depicts inward or outward or no displacements between the two time points (Figures 1 and 2). Although iterative closest point cannot be used to assess changes in shape, an iterative closest point-based algorithm coupled with CBCT images has been developed to simulate

Figure 1 Distinctions between iterative closest point (ICP) and shape correspondence in determining growth and treatment changes in craniofacial structures. Diagrammatic representation of ICP (a) and shape correspondence (b) used to compute surface distances to quantify longitudinal changes for example shown here for condylar displacement. The closest points are linear distances (shown as lines), while the shape correspondence measurements are vectors (shown as lines with direction represented by arrows). Note that the closest surface points fail to quantify the displacement when large translational changes occur. Reproduced from Hajati et al²⁶, Copyright © 2014, John Wiley and Sons.

orthodontic tooth movement with the goal of developing software to aid in orthodontic treatment planning.³⁰ The third method is shape correspondence (Figures 1 and 2), which determines the displacement of a given landmark between two time points and represents these as vectors and colour-coded maps to depict the directionality and amount of movements, respectively.^{31,32} In the future, it is likely that similar approaches will replace or complement linear and angular measurements made from 3D or planar reconstructions for determining treatment changes from CBCT images.

While 3D CBCT images are most often used to assess skeletal contributions to malocclusion, researchers are now investigating the use of these images to assess dental relationships in orthodontic patients.^{33,34} When compared with OrthoCAD® (Carlstadt, NJ) or InVivoDental™ (San Jose, CA) 3D digital models, linear measurements taken from CBCT-generated 3D digital models are sufficiently accurate to make initial diagnoses and treatment plans. Moreover, superimposing the CBCT- and OrthoCAD-generated digital models demonstrates clinically insignificant differences between the images. These findings may be surprising to those who considered the resolution of CBCT scans to be too low for accurately assessing dental relationships. While direct intraoral 3D scanners and software, such as OrthoCAD or InVivoDental, are state of the art for digital dental models, evidence suggests that clinicians can rely on current CBCT-generated dental models for accurate diagnosis and treatment planning.

Utilization of CBCT for orthodontic treatment outcomes, diagnosis and treatment planning

The justification for using CBCT in orthodontics is linked intricately to its diagnostic and therapeutic efficacies, for which research supporting its use has been performed in a relatively small subset of clinical problems that include impacted teeth, CL/P and orthognathic surgery. In the absence of such proof, a clinician still may choose to utilize the technology if there is adequate reason to believe that it likely would enhance the

diagnosis and/or alter the treatment plan. This research or clinical 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 in any of these scenarios, and based on current literature, we would anticipate that CBCT likely will provide information that could result in one or more of the following outcomes: (1) enhanced diagnosis, such as precisely localizing impacted and supernumerary teeth; (2) quantifying the magnitude of a defect or deformity, such as in patients with craniofacial anomalies; (3) improving differential diagnosis of skeletal, dental or combined malocclusions, including identifying the jaw(s) contributing to malocclusion and determining whether the discrepancy is bilateral or unilateral, such as in orthognathic surgery, asymmetry, craniofacial anomaly and open bite cases; and (4) helping to identify possible causes of malocclusions, such as the contribution of TMJ abnormalities to an open bite or asymmetry. The expected outcome of the 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.

Based on a synthesis of current scientific evidence, case reports and other available information, the sections below and Figure 3 summarise clinical scenarios where CBCT may be beneficial and ways to use this imaging modality under specific circumstances. For several of the situations, the studies aim to test the utility of CBCT in aiding diagnosis and treatment planning (e.g. impacted teeth), while for other situations, it has primarily been applied for assessing treatment outcomes [e.g. rapid maxillary expansion (RME)] or to define normal and abnormal morphology (e.g. airway). Thus it is important to recognize that the discussion below does not imply that CBCT has proven clinical utility in all case types discussed. Moreover, since orthognathic surgery and craniofacial surgery are outside the scope of this review, these topics are not discussed. Nevertheless, it is now well accepted that CBCT in combination with computerized treatment planning and 3D printed wafers (splints) is a powerful tool for treating these cases.^{35–37}

Impacted teeth: After third molars, maxillary canines are the second most commonly impacted teeth^{38,39} and are probably the most common indications for CBCT imaging in orthodontics. Indeed, of the many types of clinical situations being presented to the orthodontist, impacted teeth are ones in which CBCT has been most shown to improve diagnosis and contribute to modifications in treatment planning in a significant number of subjects.^{15,40–43} CBCT enhances the ability to localize impacted canines accurately, evaluate their proximity to other teeth and structures, determine the follicle size and the presence of pathology, estimate space conditions, assess resorption of adjacent teeth, assist in planning

Figure 2 Depiction of post-surgical three-dimensional changes in the mandible using cranial base superimposition and either iterative closest point or shape correspondence for the same patient to demonstrate how these methods result in different visual representation of treatment outcomes. (a) Semi-transparency superimposition provides a visual assessment of treatment outcomes, but the changes cannot be quantified. (b) Colour-coded map of the closest point method where blue represents inward and red outward changes with the magnitude of change shown in the accompanying colour scale. (c) Outcomes assessment with shape correspondence method depicts a colour-coded map and vectors that provide the direction and magnitude of the displacement. (d) A zoomed-in image of the chin to demonstrate the vectors from (c) in greater detail. Reproduced from Kim et al.²⁷, Copyright © 2014, John Wiley and Sons. For colour images see online: www.birpublications.org/doi/pdf/10.1259/dmfr.20140282.

surgical access and bond placement, and aid in defining optimal direction for extrusion of these teeth into the oral cavity^{43–48} (Figures 4 and 5). The findings of these studies imply that CBCT facilitates accurate 3D

depiction of the entire impacted tooth relative to neighbouring structures and teeth and assists in planning their surgical access and bond placement and in defining optimal direction for extrusion of these teeth

Figure 3 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. Reproduced from Kapila⁵, Copyright © 2014, John Wiley and Sons. dx, diagnosis; TAD, temporary anchorage device; TMJ, temporomandibular joint; tx, treatment.

into the oral cavity. For root resorption associated with impacted teeth, CBCT scans provide substantially superior visualization of roots compared with conventional 2D radiographs by eliminating superimposition artefacts and capturing 3D root structures from all

possible directions^{44–49} as discussed later (Figure 5). In fact, a recent study suggests that small volume field of view CBCT may be indicated for impacted maxillary canines if the canine inclination on a conventional 2D panoramic radiograph exceeds 30° relative

Figure 4 Pre-treatment images derived from CBCT of a patient with retained mandibular primary second molars and impacted second premolars. (a) Reconstructed panoramic radiograph shows a distally impacted mandibular right second premolar and mesially impacted mandibular left second premolar. The precise spatial positions of the mandibular second premolars and their relationships to neighbouring structures can be determined from axial (b, c), sagittal (d, e) and three-dimensional volumetric (f) reconstructions to develop a virtual treatment and biomechanical plan. Reproduced from Kapila and Nervina⁴⁸, Copyright © 2014, John Wiley and Sons.

Figure 5 Utility of CBCT in diagnosis of localization of impacted teeth and identification of associated root resorption. Two-dimensional images are prone to superimposition and other limitations, which may be overcome with CBCT that can be useful in identifying the 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 and failure of tooth to erupt, a CBCT scan was taken revealing the proximity of the impacted tooth to the lateral incisor and substantial root resorption on the lateral incisor as seen here in sagittal (c), axial (d), coronal (e) and lateral (f) volumetric representations. Given the lack of pre-treatment CBCT, it is not possible to determine the extent of pre-treatment root resorption or the contributions of treatment to the current root damage. However, because of the position of the bond on the tooth cingulum and despite desirable force vectors, it is likely that the cusp tip has continued to move along the root of the lateral incisor contributing to root resorption and difficulty in retrieval. Reproduced from Kapila and Nervina⁴⁸, Copyright © 2014, John Wiley and Sons.

to a perpendicular midline, when adjacent root resorption is suspected, and/or when canine root dilaceration is suspected on conventional panoramic radiographs.⁵⁰ The detection of abnormal anatomy of the root by CBCT, including dilacerated roots—particularly, in the buccolingual direction not seen in 2D radiographs—also may help determine the amount and direction that a dilacerated tooth can be moved or aid in the decision to extract it.⁵⁰

Besides aiding in tooth localization, CBCT is also valuable in determining the optimal site for surgical access to an impacted tooth and more importantly contributes to significantly higher confidence in a clinician's diagnosis and treatment planning than does the combination of panoramic, periapical and occlusal

radiographs that traditionally have been used for this purpose.^{40–42} Findings from these studies also demonstrate that the original treatment plans derived from 2D radiographs are changed for >25% of the impacted teeth when orthodontists viewed these teeth in CBCT images as opposed to the 2D radiographs typically used for this purpose. Thus the scientific evidence for the utility of CBCT both in refining diagnosis and modifying treatment plans for significant numbers of impacted teeth validate its use for most impacted teeth. Overall, it can be expected that the optimal and accurate utilization of information derived from CBCT to customize treatment and biomechanics for impacted teeth should result in increased efficiency and enhanced success rates for tooth retrieval.

Supernumerary teeth: The scientific evidence on the superiority of CBCT over 2D radiography for diagnosis and treatment planning of impacted teeth could be applicable to supernumerary teeth. Supernumerary teeth are extra teeth that develop anywhere in the dentition, although they are most commonly found in the anterior maxilla and are often difficult to distinguish from normal teeth.⁴² There are two imaging goals in these cases. The first goal is to precisely localize all supernumerary teeth, many of which are unerupted or may be impacted. The second goal is to detail the morphology of the supernumerary teeth. Information derived from CBCT images of unerupted supernumerary teeth could facilitate decisions on which of the teeth to retain, determination of the retrievability of those teeth and mapping the optimal surgical access to the teeth,⁵¹ as illustrated in the example in Figure 6.

Root angulation, morphology and resorption: Since root parallelism is an important goal of orthodontic treatment, its accurate determination may provide valuable information in assessing the quality of treatment outcomes and, possibly, of post-treatment stability. Root parallelism and relationships customarily are determined with panoramic radiographs that often demonstrate inaccuracies in root angulation, especially that of maxillary and mandibular anterior teeth.^{52–54} By contrast, CBCT provides more accurate root angular measurements relative to those derived from 2D radiographs.^{55–57} Nevertheless, given that panoramic radiographs provide adequate though not accurate information on

root parallelism and the low benefit to risk of a progress CBCT, using CBCT for this purpose is not indicated.

Root resorption is the occasional and undesirable sequelae of orthodontic treatment that may compromise the longevity of teeth. Root length, form and resorption have traditionally been assessed via periapical radiographs. CBCT has been shown to be at least as good as periapical radiography for determining tooth and root length.^{58,59} Furthermore, because CBCT can generate precise images of small root defects, it provides more accurate insights into root resorption and has greater sensitivity and specificity than do panoramic or other 2D radiographs in detecting these lesions.^{47,60–64} Also, relative to CBCT, panoramic radiographs underestimate the presence of external apical root resorption (EARR).^{65,66} Finally, while 2D radiographs only provide visualization of the apex and the mesial and distal root surfaces, CBCT imaging enables the visualization of buccal and lingual root surfaces. This has led to the discovery that root loss is not only present at the root apex but often presents as a slanting root loss on surfaces adjacent to the direction of tooth movement. This finding highlights the efficacy of the 3D rendering capacity of CBCT for accurate diagnosis of both EARR and other previously uncharacterized types of root resorption. Thus, in addition to the previously accepted diagnosis of EARR that is observed in 2D radiographs, high-resolution CBCT may usher in a new diagnostic criteria of root resorption affecting root surfaces visualizable by 3D but not by 2D radiographs.

Figure 6 CBCT offers important information and finer details in treatment planning of supernumerary teeth. (a) The panoramic view extracted from the CBCT scan shows the presence of a supernumerary 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 with an asterisk and arrowhead 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 three-dimensional 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 with an asterisk most closely matches the contralateral lateral incisor morphologically and dimensionally, while the tooth marked with an arrowhead is almost 1 mm larger mesiodistally than the contralateral lateral incisor. Reproduced from Kapila et al.⁴

Currently, there is no evidence that detection of moderate-to-severe EARR differs between 2D and CBCT radiography or that its discovery by CBCT during treatment would lead to a different treatment decision—typically entailing stopping the treatment at least temporarily—than if detected by 2D radiography. However, identifying buccal or lingual root resorption, which is not visualized by 2D radiography but is detectable by CBCT, could contribute to differences in pre- or in-treatment decisions. 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.

By minimizing superimposition artefacts and enabling the visualization of roots in 3D, CBCT provides superior visualization of roots compared with 2D radiographs for root resorption associated with impacted teeth^{46,47,60,67} (Figure 5). This enhanced information derived from CBCT scans compared with 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. While such treatment decisions are a logical clinical outcome arising from the utilization of CBCT, the effects of the superior information on root resorption derived from CBCT images and 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 determined.

Alveolar boundary conditions: Alveolar boundary conditions are the depth, height and morphology of alveolar bone relative to tooth root dimensions, angulation and spatial position.⁴ Alveolar 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, alveolar 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. Compromised or inadequate pre-treatment boundary conditions as well as limited ability to adapt to tooth movement may restrict or interfere with the planned or potential tooth movement, as well as the final desired spatial position and angulation of the teeth⁶⁸ (Figure 7).

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, although not perfectly owing to some of its technological limitations.^{69–71} Although CBCT provides accurate assessment of alveolar bone height, caution must be exercised in evaluating fenestrations owing to the high number of false positives in the determination of these defects.^{69,71} Despite these limitations, CBCT 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.^{72–80}

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.^{75,80} 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 Corporation, Orange, CA) self-ligating brackets on alveolar boundary conditions.⁷² 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. These findings, thus, 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 is known that buccal crown tipping during RME (also referred to as rapid palatal expansion) is accompanied by a concomitant decrease both in buccal bone thickness and buccal marginal bone height.⁷⁶ Finally, slow palatal expansion using quadhelix or Schwarz appliances decrease and increase, respectively, buccal and lingual bone thicknesses.^{73,77–79}

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.⁸¹ Similarly, post-orthodontic increase in incisal proclination is known to be a risk factor for dehiscences.⁸² Such incisor proclination-related recession may be worse in patients with thin initial symphysis bone width.^{83,84} 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.

While it is clear that CBCT scans can accurately capture the dentoalveolar complex in 3D, it is best to be selective about what cases may benefit from CBCT scans for assessing boundary conditions.^{85,86} These include cases presenting with clinically noticeable thin alveolar bone phenotypes that may not tolerate significant labio- or buccolingual displacements (Figure 7); cases with pre-existing periodontal disease; cases requiring orthodontic tooth movements that extend beyond pre-treatment alveolar boundaries; and cases where a tooth may need to be translocated past another tooth or obstruction (Figure 8). Precise information on alveolar boundary conditions may also be helpful in treatment planning cases that require moving teeth close to the alveolar boundaries such as in borderline non-

extraction cases or in situations where teeth are being decompensated, such as commonly is performed in orthognathic surgery cases.

Quantity and quality of bone and anatomical considerations in temporary anchorage device placement: TADs are often used to provide a stable anchor for the application of orthodontic forces. Because TADs can be placed nearly anywhere in the oral cavity, ensuring that they do not impinge on important structures, such as roots or nerves, is critical for safe treatment. While there is no evidence supporting the need for CBCT to treatment plan the placement of TADs, these images can prove helpful for macroanatomical analyses through visualization of neighbouring structures such as tooth roots, sinuses and nerves that can be valuable for avoiding damage or complications. CBCT can also be useful for microanatomical evaluation of the quantity and quality of cortical bone and quality of the underlying trabecular bone that may determine primary stability of TADs, which in turn, is relevant to their secondary stability over the longer term.^{87,88} Thus, CBCT could have applications where a TAD needs to be placed in sites with complex anatomical structures or relationships, or where the quality and quantity is thought to be compromised.⁸⁹ 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.^{90,91}

Quantifying cleft lip and palate defects and outcomes of alveolar bone grafts: CL/P is the most common craniofacial anomaly in humans, and it has significant impacts on affected individuals.^{92,93} Typically, orthodontists first perform rapid palatal expansion on CL/P patients at about 9 years of age prior to the placement of a bone graft at the defect site. This timing of graft placement allows the alveolar graft to heal in time for the canine to erupt into the arch. Orthodontists then align the teeth, open space for implants and/or prepare the patients for orthognathic surgery, as needed. Missing or dysmorphic incisors are common at the cleft site. Therefore, radiographs of the dentition at an early age are needed to examine the number and morphology of the patient's teeth, which provides the craniofacial team time to treatment plan possible extractions, restorative dentistry, orthodontics to open or close space and implants. While 2D radiographs have been used for this purpose, CBCT may provide more precise information on the numbers, quality and location of teeth in proximity of the cleft site,⁹⁴ eruption status and path of canines in grafted cleft sites,⁹⁵ and diagnosing for implant placement.⁹⁶

At a later stage of treatment pre-alveolar graft radiographs provide the orthodontist and the surgeon with information on how much expansion and graft material will be needed to provide sufficient space for

the canine to erupt. Although conventional 2D radiographs have been used for these purposes, the ability to discern the precise volume of the post-expansion defect and therefore optimally plan the surgery and amount of donor tissue needed may provide relative advantages of using CBCT over 2D radiographs. CBCT images are valuable for determining the volume of the alveolar defect and, therefore, the amount of bone needed for grafting in patients with CL/P and for determining the success of bone fill following surgery⁹⁶⁻⁹⁸ (Figure 9). 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.⁹⁹ Additionally, the CBCT images enable the visualization of the 3D morphology of the bone bridge, the relationship between the bone bridge and roots of the neighbouring teeth and their periodontal condition. Finally, CBCT can be useful for diagnosis and treatment of impacted canines that are common in patients with CL/P and their paths of eruption through grafted bone sites.^{95,96,98-102}

Temporomandibular joint morphology and pathology contributing to malocclusion: Limited opening or excursive movements, joint pain and joint sounds are indicators of various TMJ pathologies, including osteoarthritis, rheumatoid arthritis, idiopathic condylar resorption and other less common TMJ disorders. The progressive radiographic changes common to most of these TMJ diseases include irregular and/or thickened cortical outlines (sclerosis), erosions, osteophyte formation, subchondral cysts, and flattening and narrowing of the joint space.^{103,104} Optimizing the visualization of these changes could be useful in discerning the magnitude of degenerative changes and distinguishing the finer details of joint pathology critical for accurate diagnosis and referring the patients to the appropriate specialists prior to commencing orthodontic treatment.

As expected, CBCT images provide clinicians with more accurate anatomic detail of the TMJ than do conventional 2D panoramic radiographs.^{105,106} CBCT facilitates visualization of minor to overt osseous hard tissue changes and congruency of articulating surfaces resulting from pathology and adaptive processes and allows for accurate detection and evaluation of pathological changes.^{107,108} CBCT has been shown to be more efficacious than conventional tomography and MRI in detecting osseous changes.^{109,110} Finally, comparison of asymptomatic control and osteoarthritic TMJs by shape correspondence also has shown significant differences between the morphologies of healthy and degenerative condyles and significant correlations between the intensity of pain and local anatomic changes in the condyle¹¹⁰ (Figure 10). While these findings suggest the potential utility of CBCT as a diagnostic aid in TMJ osteoarthritis, it is important to understand that structural bony changes of the TMJ

Figure 7 CBCT images of incisors with thin alveolar boundary condition biotype before (a–e) and after (f–j) non-extraction orthodontic treatment involving anterior expansion and flaring of the incisors. Sagittal sections along the long axis of the mandibular left lateral (a, f), left central (b, g), right central (c, h) and right lateral (d, i) incisors show considerable loss of alveolar buccal bone following treatment. Pre- and post-treatment axial slices (e, j) demonstrate protrusion of mandibular incisors at the end of orthodontic treatment. To make valid comparisons, the sections in post-treatment images were taken as close as possible to those in pre-treatment images. Reproduced from Kapila and Nervina⁶⁸, Copyright © 2014, John Wiley and Sons.

alone do not reveal whether or not the disease is active and no direct correlation between TMJ morphological changes and clinical findings in osteoarthritis or other arthritides exists. Although CBCT alone without an accurate history and clinical findings cannot distinguish between these disorders, a recent study confirms that clinicians are more likely to change their diagnosis of TMJ disease after viewing CBCT images of symptomatic subjects.¹¹¹

While relatively infrequent, some patients who have TMJ pathologies, including degenerative joint disease, or developmental disorders, such as condylar hyperplasia, hypoplasia or aplasia, undergo adverse morphological and functional changes that include progressive bite changes, dental and skeletal compensations and limitation or deviation of jaw movements^{103,112–114} 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, decrease in ipsilateral mandibular growth and contribute to compensations in the maxilla, tooth position, occlusion and cranial base.^{112–115} 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.^{103,112–114} 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. By contrast, CBCT

images by allowing the concurrent visualization of the TMJs and assessment of the maxillo-mandibular-spatial relationships and occlusion provide the opportunity to visualize and quantify the local and regional effects associated with the TMJ abnormalities.

Airway morphology, vertical malocclusion and obstructive sleep apnoea: A constricted pharyngeal airway is considered a potential contributor to vertical malocclusion in children who develop a mouth breathing habit.¹¹⁶ In addition, there is a growing interest among orthodontists in airway morphology, its relationship to OSA and the effects of orthodontic treatment on OSA.^{117–119} A constricted airway, especially in children with enlarged adenoids and tonsils, is often diagnosed clinically. Conventional 2D lateral cephalographs are also sufficient to diagnose airway constriction in the sagittal plane and have been used for some of the most recent studies on airway changes following orthodontic treatment.^{120,121} However, the possibility that volume or cross-sectional area may be a better measure of airway constriction has been proposed, which requires CBCT, rather than conventional images.¹²²

While CBCT is generally used to image mineralized tissues, it can also be used to accurately image the airway, which allows clinicians to measure cross-sectional area, minimum cross section and total volume of the patient's airway^{123–125} (Figure 11). Initial investigations on airway patency, function and disorders utilizing CBCT have provided preliminary answers, including dimensions of normal airway anatomy in adults,^{122,126} relationship

Figure 8 Pre-treatment CBCT images of a patient with bilateral complete transpositions of the maxillary canines and first premolars demonstrate the possible restrictions placed by boundary conditions on treatment options. Three-dimensional volumetric reconstructions of the buccal aspect of the right (a) and left (b) sides showing the complete transpositions of the canines and first premolars and detailing the spatial positions of the transposed teeth and their relationships to each other and neighbouring structures. (c) Coronal section demonstrating the proximity of the roots of the translocated teeth to each other and to alveolar boundaries. Lines d, e and f in this panel represent locations at which axial cross-sections of the images, depicted in d, e and f, respectively, were reconstructed to visualize the relationships of the crowns and roots of the transposed teeth to each other. Axial section at mid-crown (d), cemento-enamel junction (e) and mid-root (f) of the transposed teeth demonstrate details of tooth-tooth and tooth-bone relationships. These images can be used to establish the treatment decisions on extractions if needed, and in non-extraction cases, whether to retain the transposed teeth closest to the current locations or move them into their correct locations in the arch. The images are also useful for biomechanics planning in any of the latter two treatment options that may include proactively moving tooth roots out of the path to be used to relocate the transposed tooth or root, determining if the boundary conditions will permit such movements, planning the force systems, and vector(s) of movements. These considerations taken together can help define the prognosis of moving transposed teeth or roots past each other to arrive at the optimal treatment choice. Reproduced from Kapila and Nervina⁴⁸, Copyright © 2014, John Wiley and Sons.

of 2D to 3D measurements,¹²⁷ differences in airway morphology in subjects with OSA and non-OSA,^{128–130} the effects of extractions on 3D pharyngeal volume and structure,¹³¹ and the consequences of RME^{132–135} and orthognathic surgery on airway dimensions.^{136,137} Several of these studies show no relationships between 2D linear dimensions and 3D cross-sectional areas of the airway, which suggests that the use of 2D data may not be valid for assessing airway patency.

Early thinking in orthodontics suggested that a constricted pharyngeal airway may contribute to mouth breathing in children, which then would lead to a steep

mandibular plane angle and an anterior open bite tendency.¹¹⁶ Two recent studies using CBCT imaging to test this hypothesis have generated conflicting results with one study showing no relationship between facial pattern and airway volume, while the other study demonstrated the existence of such a relationship.^{122,126} The discrepancies in the findings of the two studies highlight the need to use a standardized protocol for measuring airway volumes. Perhaps consistent with this lack of agreement is the fact that there are no studies demonstrating that qualitative or quantitative assessments of CBCT images are capable of predicting OSA accurately.

Figure 9 Volume rendering of CBCT scans of an individual with a unilateral cleft lip and palate (a) before and (b) after alveolar bone grafting. With CBCT imaging, assessing the morphology, locating the position and determining the developmental stage of the unerupted maxillary left canine (arrow) permit the orthodontist and surgeon to time the placement of the alveolar graft ahead of canine eruption. Sufficient lead time allows the graft to mature and gives the orthodontist sufficient time for arch development to better support the canine as it erupts into the arch. Reproduced from Oberoi et al⁹⁸, Copyright © 2014, John Wiley and Sons.

CBCT imaging has been used to investigate the efficacy of RME and surgery as treatment options for a constricted airway. Since many patients with OSA have a reduced transverse airway dimension pointing to the potential contribution of this finding to airway patency, the effects of RME treatment on nasal cavity and upper pharyngeal airway dimensions has been studied in 3D.^{118,132,138} RME is generally shown to increase maxillary and nasal widths but not pharyngeal airway volume. This suggests that the effects of palatal expansion do not extend far enough

posteriorly to significantly improve breathing in OSA patients but may be beneficial for patients with mild respiratory problems owing to nasal constriction. Likewise, orthognathic surgery effects on pharyngeal airway space has been evaluated with CBCT images taken on Class II¹³⁹ and Class III^{140,141} patients. As would be predicted, surgical correction of Class II patients results in an increase in pharyngeal airway volume, while Class III correction reduces upper airway volume. The clinical effects that increased pharyngeal airway volume from

Figure 10 Statistical significance maps of correlations between local morphological differences in condylar shape and pain intensity. Significance maps show statistically significant correlations between pain intensity and morphologic differences in the superior surface of the condyle (a) and the lateral and posterior surfaces of the condyle (b). The colour scale at the bottom represents correlation p -values between pain and morphological variance in the condyle relative to an average condyle. Reproduced from Majati et al²⁶, Copyright © 2014, John Wiley and Sons. For colour image please online: www.birpublications.org/doi/abs/10.1259/dmfr/20140282.

Figure 11 Three-dimensional (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. Reproduced from Kapila⁵, Copyright © 2014, John Wiley and Sons.

these procedures has on respiratory function have not yet been determined.

Maxillary transverse dimension and maxillary expansion: Maxillary transverse deficiency is a common cause of malocclusions that are notable for posterior crossbites and are often accompanied by crowding and/or increased overjet. Correction of these occlusal and maxillary arch anomalies with RME is indicated in growing patients to widen the maxillary transverse dimension primarily through widening the mid-palatal suture. This goal of RME treatment in these cases is to re-establish the correct posterior transverse occlusion and increase the arch length to relieve crowding through skeletal expansion and/or dental tipping.

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. Studies to date on RME have primarily focused on determining treatment outcomes rather than the utility of CBCT in diagnosis and treatment planning of transverse discrepancies. Specifically, CBCT has been used to address two questions related to RME treatment, namely how expansion forces affect different regions of the maxilla and the effect of age on the relative magnitude of skeletal expansion *vs* dental tipping.^{74,76,142,143} These studies show that tooth-borne RME treatment in growing children result in separation of several circum-maxillary sutures contributing to an increase in not only the transverse dimension but also in the sagittal and vertical dimension.^{142,143} Not surprisingly, younger children (6–8 years old) demonstrate greater skeletal expansion than older children (9–11 years old) who show greater dental tipping following RME treatment.^{144,145} Treatment with four-banded maxillary expanders also reveal 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 in the posterior maxilla.^{74,76,146} These differences in findings between skeletal and overall expansion result from increasingly greater alveolar bone bending and buccal crown tip going back from the first premolar to the

first molar. Additionally, there is an associated increase in nasal width and decrease in maxillary sinus width.⁷⁴ Taken together, these findings confirm that besides sutural expansion, RME produces both dental and alveolar tipping, and suggests that much of post-RME relapse may occur owing to “rebound” from the alveolar bending and dental tipping, since these two modalities of expansion are difficult to retain. These findings also imply that RME treatment has the potential for moving teeth through cortical bone particularly if it is accompanied by dental movements as in older patients, or if the roots are initially positioned too close to the alveolar boundary.¹⁴⁷ In contrast to expansion using the fixed RME appliance, a removable Schwarz appliance achieves expansion in both arches through alveolar buccal tipping.^{77–79}

From the perspective of utility of CBCT as a diagnostic and treatment planning tool for transverse corrections, recent attempts have been made to understand if sutural maturation could help predict the relative magnitudes of skeletal *vs* dental expansion expected in patients undergoing RME with inconclusive findings.¹⁴⁸ Also, early attempts have been made to quantify pre-treatment transverse dental inclinations from CBCT coronal segment reconstructions to discern the relative magnitudes of dental and skeletal movements needed to correct transverse discrepancies, which might prove valuable if optimal biomechanics can then be applied to achieve the desired plans.¹⁴⁹

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 data from 3D scans have in modifying or enhancing diagnosis and altering or refining treatment plans when compared with decisions made with 2D radiographs. In this context, studies confirm that CBCT contributes to enhanced diagnosis, changes in treatments and greater confidence in treatment decisions by clinicians in cases with impactions, CL/P or severe skeletal

malocclusions.^{40–42,95–102,150} It is likely that future research will provide evidence for efficacy of CBCT in additional clinical situations further addressing the question of when CBCT should be used, and also will help for enhanced diagnosis and detailed treatment planning of specific types of cases. For example, while CBCT scans are valuable for accurate 3D localization of impacted teeth, it is becoming increasingly clear that this information is equally valuable for optimizing the biomechanics plan to ensure that the direction of traction travels the shortest possible path while minimizing damage to adjacent teeth.⁴⁸

CBCT research is also beginning to provide critical information on potential new diagnostic categories such as alveolar bone boundary conditions and root integrity in dimensions not observed in that of 2D radiographs. Current orthodontic treatment entails moving teeth as efficiently as possible within the constraints of the bone encasing the roots without damaging the roots or adjacent structures. Determining the dynamic limits of the alveolar boundary conditions and root remodelling during treatment for each patient would be a major step towards providing individualized orthodontic treatment. This would, of course, require significant inroads in determining the genetic contributions to each patient's risk for inadequate alveolar boundary remodelling and root resorption. Nonetheless, as further scientific evidence on the limitations imposed by boundary conditions and risks for root resorption on orthodontic treatment become available, clinicians may be able to answer important treatment planning questions such as (1) can the desired tooth movement be accomplished within the existing boundary conditions without damaging the roots or adjacent structures? (2) Will boundary conditions or root morphology be affected positively or negatively by skeletal or dentoalveolar 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) How are alveolar bone adaptability and risks for root resorption affected by age, periodontal health and the pre-treatment bone and anatomic phenotype of the patient? Additionally, it is possible that high-resolution CBCT scans might offer definitive diagnostic information on tooth ankylosis, 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.¹⁵⁰

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 gathered on 3D craniofacial morphology in health and disease, treatment outcomes and the efficacy of CBCT in diagnosis and treatment planning. Although CBCT continues to gain popularity, its use currently is recommended in cases in which clinical examination supplemented with conventional radiography cannot supply satisfactory diagnostic information. To date, this applies to impacted teeth, CL/P and orthognathic or craniofacial surgery patients. CBCT on other types of cases can also 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. Based on research evidence, orthodontists are advised to use their best clinical judgment when prescribing radiographs, including CBCT scans, to obtain the most relevant data using the least ionizing radiation possible.

References

1. Mozzo P, Procacci C, Tacconi A, Martini PT, Andreis IA. A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *Eur Radiol* 1998; **8**: 1558–64.
2. Hatcher DC. Operational principles for cone-beam computed tomography. *J Am Dent Assoc* 2010; **141**(Suppl. 3): 3S–6S.
3. Kapila S, Farman AG. Craniofacial imaging in the 21st century. Proceedings of the 2002 COAST Conference, Asilomar Conference Center, Pacific Grove, California. *Orthod Craniofac Res* 2003; **6**: 7–8.
4. Kapila S, Conley RS, Harrell WE Jr. The current status of cone beam computed tomography imaging in orthodontics. *Dentomaxillofac Radiol* 2011; **40**: 24–34. doi: [10.1259/dmfr/12615645](https://doi.org/10.1259/dmfr/12615645)
5. Kapila S. Contemporary concepts on cone-beam computed tomography in orthodontics. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 5–42.
6. American Dental Association Council on Scientific Affairs. The use of dental radiographs: update and recommendations. *J Am Dent Assoc* 2006; **137**: 1304–12.
7. European Commission. Item 4.2. The developing dentition in protection radiation No. 172. Cone beam CT dental maxillofacial radiology (evidence-based guidelines). 2011. Available from: http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/172.pdf
8. Janssens A, Horner K, Rushton V, Walker A, Tsikakis K, Hirschmann PN, et al. Radiation protection: European guidelines on radiation protection in dental radiology. The safe use radiographs dental practice. 2004. Available from: http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/136.pdf
9. SEDENTEXCT. Chapter 4. Justification and referral criteria. The developing dentition. Radiation protection: cone beam CT for dental and maxillofacial radiology (evidence-based guidelines). 2011. Available from: http://www.eadmfir.info/sites/default/files/guidelines_final.pdf
10. US Department of Health and Human Services, Public Health Service, Food and Drug Administration and American Dental Association, Council on Dental Benefit Programs, Council on Scientific Affairs. The selection of patients for dental radiographic examinations. 2004. Available from: <http://www.ada.org/prof/resources/topics/radiography.asp>
11. American Academy of Oral and Maxillofacial Radiology. Clinical recommendations regarding use of cone beam computed tomography in orthodontics. [corrected]. Position statement by

- the American Academy of Oral and Maxillofacial Radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013; **116**: 238–57. doi: [10.1016/j.oooo.2013.06.002](https://doi.org/10.1016/j.oooo.2013.06.002)
12. Isaacson KG, Thom AR, Horner K, Whaites E. *Orthodontic radiographs—guidelines for the use of radiographs in clinical orthodontics*. 3rd edn. London, UK: British Orthodontic Society; 2008.
13. Durao AR, Pittayapat P, Rockenbach MI, Olszewski R, Ng S, Ferreira AP, et al. Validity of 2D lateral cephalometry in orthodontics: a systematic review. *Prog Orthod* 2013; **14**: 31. doi: [10.1186/2196-1042-14-31](https://doi.org/10.1186/2196-1042-14-31)
14. Pittayapat P, Limchaichana-Bolstad N, Willems G, Jacobs R. Three-dimensional cephalometric analysis in orthodontics: a systematic review. *Orthod Craniofac Res* 2014; **17**: 69–91. doi: [10.1111/ocr.12034](https://doi.org/10.1111/ocr.12034)
15. Rischen RJ, Breuning KH, Bronkhorst EM, Kuijpers-Jagtman AM. Records needed for orthodontic diagnosis and treatment planning: a systematic review. *PLoS One* 2013; **8**: e74186. doi: [10.1371/journal.pone.0074186](https://doi.org/10.1371/journal.pone.0074186)
16. International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. ICRP publication 60. *Ann ICRP* 1991; **21**: 1–201.
17. International Commission on Radiological Protection. The 2007 recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP* 2008; **37**: 1–332.
18. Kumar V, Ludlow JB, Mol A, Cevidanes L. Comparison of conventional and cone beam CT synthesized cephalograms. *Dentomaxillofac Radiol* 2007; **36**: 263–9.
19. Moshiri M, Scarfe WC, Hilgers ML, Scheetz JP, Silveira AM, Farman AG. Accuracy of linear measurements from imaging plate and lateral cephalometric images derived from cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2007; **132**: 550–60.
20. Stratemann SA, Huang JC, Maki K, Hatcher DC, Miller AJ. Evaluating the mandible with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2010; **137**: S58–70. doi: [10.1016/j.ajodo.2009.01.025](https://doi.org/10.1016/j.ajodo.2009.01.025)
21. Lee M, Kanavakis G, Miner RM. Newly defined landmarks for a three-dimensionally based cephalometric analysis: a retrospective cone-beam computed tomography scan review. *Angle Orthod* May 2014. Epub ahead of print.
22. Jung YJ, Kim MJ, Baek SH. Hard and soft tissue changes after correction of mandibular prognathism and facial asymmetry by mandibular setback surgery: three-dimensional analysis using computerized tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **107**: 763–71.e8.
23. Kim YI, Jung YH, Cho BH, Kim JR, Kim SS, Son WS, et al. The assessment of the short- and long-term changes in the condylar position following sagittal split ramus osteotomy (SSRO) with rigid fixation. *J Oral Rehabil* 2010; **37**: 262–70. doi: [10.1111/j.1365-2842.2009.02056.x](https://doi.org/10.1111/j.1365-2842.2009.02056.x)
24. Kim YI, Cho BH, Jung YH, Son WS, Park SB. 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 Surg Oral Med Oral Pathol Oral Radiol Endod* 2011; **111**: 681–7. doi: [10.1016/j.tripleo.2010.08.001](https://doi.org/10.1016/j.tripleo.2010.08.001)
25. Cevidanes LH, Bailey LJ, Tucker SF, Styner MA, Mol A, Phillips CL, et al. Three-dimensional cone-beam computed tomography for assessment of mandibular changes after orthognathic surgery. *Am J Orthod Dentofacial Orthop* 2007; **131**: 44–50.
26. Hajati A-K, Cevidanes LHS, Iwasaki L, Nickel J, Kapila SD. Application of 3D TMJ imaging to TMJDs, TMJ functional analyses and orthodontic treatment outcomes. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 247–72.
27. Kim Y-J, Park Y-H, de Paula LK, Conley RS. 3D assessment of orthognathic surgical treatment outcomes. In: Kapila S (ed).
- Cone beam computed tomography in Orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 463–83.
28. Almeida RC, Cevidanes LH, Carvalho FA, Motta AT, Almeida MA, Styner M, et al. Soft tissue response to mandibular advancement using 3D CBCT scanning. *Int J Oral Maxillofac Surg* 2011; **40**: 353–9. doi: [10.1016/j.ijom.2010.11.018](https://doi.org/10.1016/j.ijom.2010.11.018)
29. Motta AT, Cevidanes LH, Carvalho FA, Almeida MA, Phillips C. Three-dimensional regional displacements after mandibular advancement surgery: one year of follow-up. *J Oral Maxillofac Surg* 2011; **69**: 1447–57. doi: [10.1016/j.joms.2010.07.018](https://doi.org/10.1016/j.joms.2010.07.018)
30. Yau HT, Yang TJ, Chen YC. Tooth model reconstruction based upon data fusion for orthodontic treatment simulation. *Comput Biol Med* 2014; **48**: 8–16. doi: [10.1016/j.combiomed.2014.02.001](https://doi.org/10.1016/j.combiomed.2014.02.001)
31. Paniagua B, Cevidanes L, Zhu H, Styner M. Outcome quantification using SPHARM-PDM toolbox in orthognathic surgery. *Int J Comput Assist Radiol Surg* 2011; **6**: 617–26. doi: [10.1007/s11548-010-0539-z](https://doi.org/10.1007/s11548-010-0539-z)
32. Nguyen T, Cevidanes L, Paniagua B, Zhu H, Koerich L, De Clerck H. Use of shape correspondence analysis to quantify skeletal changes associated with bone-anchored Class III correction. *Angle Orthod* 2014; **84**: 329–36. doi: [10.2319/041513-288.1](https://doi.org/10.2319/041513-288.1)
33. Lightheart KG, English JD, Kau CH, Akyalcin S, Bussa HI Jr, McGrory KR, et al. Surface analysis of study models generated from OrthoCAD and cone-beam computed tomography imaging. *Am J Orthod Dentofacial Orthop* 2012; **141**: 686–93. doi: [10.1016/j.ajodo.2011.12.019](https://doi.org/10.1016/j.ajodo.2011.12.019)
34. Creed B, Kau CH, English JD, Xia JJ, Lee RP. A comparison of the accuracy of linear measurements obtained from cone beam computerized tomography images and digital models. *Semin Orthod* 2011; **17**: 49–56.
35. Aboul-Hosn Centenero S, Hernandez-Alfaro F. 3D planning in orthognathic surgery: CAD/CAM surgical splints and prediction of the soft and hard tissues results—our experience in 16 cases. *J Craniomaxillofac Surg* 2012; **40**: 162–8. doi: [10.1016/j.jcms.2011.03.014](https://doi.org/10.1016/j.jcms.2011.03.014)
36. Zinser MJ, Mischkowski RA, Sailer HF, Zoller JE. Computer-assisted orthognathic surgery: feasibility study using multiple CAD/CAM surgical splints. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012; **113**: 673–87. doi: [10.1016/j.oooo.2011.11.009](https://doi.org/10.1016/j.oooo.2011.11.009)
37. Metzger MC, Hohlweg-Majert B, Schwarz U, Teschner M, Hammer B, Schmelzeisen R. Manufacturing splints for orthognathic surgery using a three-dimensional printer. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; **105**: e1–7. doi: [10.1016/j.tripleo.2007.07.040](https://doi.org/10.1016/j.tripleo.2007.07.040)
38. Bedoya MM, Park JH. A review of the diagnosis and management of impacted maxillary canines. *J Am Dent Assoc* 2009; **140**: 1485–93.
39. Manne R, Gandikota C, Juvvadi SR, Rama HR, Anche S. Impacted canines: etiology, diagnosis, and orthodontic management. *J Pharm Bioallied Sci* 2012; **4**: S234–8. doi: [10.4103/0975-7406.100216](https://doi.org/10.4103/0975-7406.100216)
40. Botticelli S, Verna C, Cattaneo PM, Heidmann J, Melsen B. Two- versus three-dimensional imaging in subjects with unerupted maxillary canines. *Eur J Orthod* 2011; **33**: 344–9. doi: [10.1093/ejo/cjq102](https://doi.org/10.1093/ejo/cjq102)
41. Haney E, Gansky SA, Lee JS, Johnson E, Maki K, Miller AJ, et al. Comparative analysis of traditional radiographs and cone-beam computed tomography volumetric images in the diagnosis and treatment planning of maxillary impacted canines. *Am J Orthod Dentofacial Orthop* 2010; **137**: 590–7. doi: [10.1016/j.ajodo.2008.06.035](https://doi.org/10.1016/j.ajodo.2008.06.035)
42. Katheria BC, Kau CH, Tate R, Chen JW, English J, Bouquot J. Effectiveness of impacted and supernumerary tooth diagnosis from traditional radiography versus cone beam computed tomography. *Pediatr Dent* 2010; **32**: 304–9.
43. Walker L, Enciso R, Mah J. Three-dimensional localization of maxillary canines with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2005; **128**: 418–23.
44. Lai CS, Bornstein MM, Mock L, Heuberger BM, Dietrich T, Katsaros C. Impacted maxillary canines and root resorptions of

- neighbouring teeth: a radiographic analysis using cone-beam computed tomography. *Eur J Orthod* 2013; **35**: 529–38. doi: [10.1093/ejo/cjs037](https://doi.org/10.1093/ejo/cjs037)
45. Oberoi S, Knueppel S. Three-dimensional assessment of impacted canines and root resorption using cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012; **113**: 260–7. doi: [10.1016/j.tripleo.2011.03.035](https://doi.org/10.1016/j.tripleo.2011.03.035)
 46. Alqerban A, Jacobs R, Fieuws S, Willems G. Comparison of two cone beam computed tomographic systems versus panoramic imaging for localization of impacted maxillary canines and detection of root resorption. *Eur J Orthod* 2011; **33**: 93–102. doi: [10.1093/ejo/cjq034](https://doi.org/10.1093/ejo/cjq034)
 47. Alqerban A, Jacobs R, Lambrechts P, Loozen G, Willems G. Root resorption of the maxillary lateral incisor caused by impacted canine: a literature review. *Clin Oral Investig* 2009; **13**: 247–55. doi: [10.1007/s00784-009-0262-8](https://doi.org/10.1007/s00784-009-0262-8)
 48. Kapila S, Nervina JM. 3D Image-aided diagnosis and treatment of impacted and transposed teeth. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 349–81.
 49. Nervina JM, Kapila S. Assessment of root position and morphology by cone beam computed tomography. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 319–48.
 50. Wriedt S, Jaklin J, Al-Nawas B, Wehrbein H. Impacted upper canines: examination and treatment proposal based on 3D versus 2D diagnosis. *J Orofac Orthop* 2012; **73**: 28–40. doi: [10.1007/s00056-011-0058-8](https://doi.org/10.1007/s00056-011-0058-8)
 51. Toureno L, Park JH, Cederberg RA, Hwang EH, Shin JW. Identification of supernumerary teeth in 2D and 3D: review of literature and a proposal. *J Dent Educ* 2013; **77**: 43–50.
 52. Garcia-Figueroa MA, Raboud DW, Lam EW, Heo G, Major PW. Effect of buccolingual root angulation on the mesiodistal angulation shown on panoramic radiographs. *Am J Orthod Dentofacial Orthop* 2008; **134**: 93–9. doi: [10.1016/j.ajodo.2006.07.034](https://doi.org/10.1016/j.ajodo.2006.07.034)
 53. McKee IW, Williamson PC, Lam EW, Heo G, Glover KE, Major PW. The accuracy of 4 panoramic units in the projection of mesiodistal tooth angulations. *Am J Orthod Dentofacial Orthop* 2002; **121**: 166–75.
 54. Owens AM, Johal A. Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. *Angle Orthod* 2008; **78**: 475–81. doi: [10.2319/040107-161.1](https://doi.org/10.2319/040107-161.1)
 55. Bouwens DG, Cevidanes L, Ludlow JB, Phillips C. Comparison of mesiodistal root angulation with posttreatment panoramic radiographs and cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2011; **139**: 126–32. doi: [10.1016/j.ajodo.2010.05.016](https://doi.org/10.1016/j.ajodo.2010.05.016)
 56. Peck JL, Sameshima GT, Miller A, Worth P, Hatcher DC. Mesiodistal root angulation using panoramic and cone beam CT. *Angle Orthod* 2007; **77**: 206–13.
 57. Van Elslande D, Heo G, Flores-Mir C, Carey J, Major PW. Accuracy of mesiodistal root angulation projected by cone-beam computed tomographic panoramic-like images. *Am J Orthod Dentofacial Orthop* 2010; **137**: S94–9. doi: [10.1016/j.ajodo.2009.02.028](https://doi.org/10.1016/j.ajodo.2009.02.028)
 58. Lund H, Grondahl K, Grondahl HG. Cone beam computed tomography for assessment of root length and marginal bone level during orthodontic treatment. *Angle Orthod* 2010; **80**: 466–73. doi: [10.2319/072909-427.1](https://doi.org/10.2319/072909-427.1)
 59. Sherrard JF, Rossouw PE, Benson BW, Carrillo R, Buschang PH. Accuracy and reliability of tooth and root lengths measured on cone-beam computed tomographs. *Am J Orthod Dentofacial Orthop* 2010; **137**: S100–8. doi: [10.1016/j.ajodo.2009.03.040](https://doi.org/10.1016/j.ajodo.2009.03.040)
 60. Alqerban A, Jacobs R, Souza PC, Willems G. *In-vitro* comparison of 2 cone-beam computed tomography systems and panoramic imaging for detecting simulated canine impaction-induced external root resorption in maxillary lateral incisors. *Am J Orthod Dentofacial Orthop* 2009; **136**: 764 e1–11; discussion 764–5. doi: [10.1016/j.ajodo.2009.03.036](https://doi.org/10.1016/j.ajodo.2009.03.036)
 61. Durack C, Patel S, Davies J, Wilson R, Mannocci F. Diagnostic accuracy of small volume cone beam computed tomography and intraoral periapical radiography for the detection of simulated external inflammatory root resorption. *Int Endodont J* 2011; **44**: 136–47. doi: [10.1111/j.1365-2591.2010.01819.x](https://doi.org/10.1111/j.1365-2591.2010.01819.x)
 62. Ponder S. Diagnostic capability of CBCT in determining external root resorption: a volumetric and linear analysis. MSc thesis. University of Michigan School of Dentistry; 2011.
 63. Ponder SN, Benavides E, Kapila S, Hatch NE. Quantification of external root resorption by low- vs high-resolution cone-beam computed tomography and periapical radiography: a volumetric and linear analysis. *Am J Orthod Dentofacial Orthop* 2013; **143**: 77–91. doi: [10.1016/j.ajodo.2012.08.023](https://doi.org/10.1016/j.ajodo.2012.08.023)
 64. Ren H, Chen J, Deng F, Zheng L, Liu X, Dong Y. Comparison of cone-beam computed tomography and periapical radiography for detecting simulated apical root resorption. *Angle Orthod* 2013; **83**: 189–95. doi: [10.2319/050512-372.1](https://doi.org/10.2319/050512-372.1)
 65. Dudic A, Giannopoulou C, Leuzinger M, Kiliaridis S. Detection of apical root resorption after orthodontic treatment by using panoramic radiography and cone-beam computed tomography of super-high resolution. *Am J Orthod Dentofacial Orthop* 2009; **135**: 434–7. doi: [10.1016/j.ajodo.2008.10.014](https://doi.org/10.1016/j.ajodo.2008.10.014)
 66. Segal GR, Schiffman PH, Tuncay OC. Meta analysis of the treatment-related factors of external apical root resorption. *Orthod Craniofac Res* 2004; **7**: 71–8.
 67. Alqerban A, Jacobs R, Fieuws S, Nackaerts O; SEDENTEXCT Project Consortium, Willems G. Comparison of 6 cone-beam computed tomography systems for image quality and detection of simulated canine impaction-induced external root resorption in maxillary lateral incisors. *Am J Orthod Dentofacial Orthop* 2011; **140**: e129–39. doi: [10.1016/j.ajodo.2011.03.021](https://doi.org/10.1016/j.ajodo.2011.03.021)
 68. Kapila S, Nervina JM. Alveolar boundary conditions in orthodontic diagnosis and treatment planning. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 293–316.
 69. Leung CC, Palomo L, Griffith R, Hans MG. Accuracy and reliability of cone-beam computed tomography for measuring alveolar bone height and detecting bony dehiscences and fenestrations. *Am J Orthod Dentofacial Orthop* 2010; **137**: S109–19. doi: [10.1016/j.ajodo.2009.07.013](https://doi.org/10.1016/j.ajodo.2009.07.013)
 70. Molen AD. Considerations in the use of cone-beam computed tomography for buccal bone measurements. *Am J Orthod Dentofacial Orthop* 2010; **137**: S130–5. doi: [10.1016/j.ajodo.2010.01.015](https://doi.org/10.1016/j.ajodo.2010.01.015)
 71. Patcas R, Muller L, Ullrich O, Peltomaki T. Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth. *Am J Orthod Dentofacial Orthop* 2012; **141**: 41–50. doi: [10.1016/j.ajodo.2011.06.034](https://doi.org/10.1016/j.ajodo.2011.06.034)
 72. Cattaneo PM, Treccani M, Carlsson K, Thorgeirsson T, Myrda A, Cevidanes LH, et al. 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. *Orthod Craniofac Res* 2011; **14**: 222–33. doi: [10.1111/j.1601-6343.2011.01527.x](https://doi.org/10.1111/j.1601-6343.2011.01527.x)
 73. Corbridge JK, Campbell PM, Taylor R, Ceen RF, Buschang PH. Transverse dentoalveolar changes after slow maxillary expansion. *Am J Orthod Dentofacial Orthop* 2011; **140**: 317–25. doi: [10.1016/j.ajodo.2010.06.025](https://doi.org/10.1016/j.ajodo.2010.06.025)
 74. Garrett BJ, Caruso JM, Rungcharassaeng K, Farrage JR, Kim JS, Taylor GD. Skeletal effects to the maxilla after rapid maxillary expansion assessed with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2008; **134**: 8–9. doi: [10.1016/j.ajodo.2008.06.004](https://doi.org/10.1016/j.ajodo.2008.06.004)
 75. Johnson DP. Effects of curve of Wilson correction and pre-treatment boundary conditions on quantitative changes in alveolar bone morphology. MSc thesis. University of Michigan School of Dentistry; 2011.
 76. Rungcharassaeng K, Caruso JM, Kan JY, Kim J, Taylor G. Factors affecting buccal bone changes of maxillary posterior

- teeth after rapid maxillary expansion. *Am J Orthod Dentofacial Orthop* 2007; **132**: 428.e1–8.
77. Tai K, Hotokezaka H, Park JH, Tai H, Miyajima K, Choi M, et al. Preliminary cone-beam computed tomography study evaluating dental and skeletal changes after treatment with a mandibular Schwarz appliance. *Am J Orthod Dentofacial Orthop* 2010; **138**: 262 e1–11; discussion 262–3. doi: [10.1016/j.ajodo.2010.02.023](https://doi.org/10.1016/j.ajodo.2010.02.023)
78. Tai K, Park JH. Dental and skeletal changes in the upper and lower jaws after treatment with Schwarz appliances using cone-beam computed tomography. *J Clin Pediatr Dent* 2010; **35**: 111–20.
79. Tai K, Park JH, Mishima K, Shin JW. 3-Dimensional cone-beam computed tomography analysis of transverse changes with Schwarz appliances on both jaws. *Angle Orthod* 2011; **81**: 670–7. doi: [10.2319/110910-655.1](https://doi.org/10.2319/110910-655.1)
80. Welmerink AD. Effects of non-extraction orthodontic therapy and boundary conditions on quantitative changes in alveolar bone morphology. MSc thesis. University of Michigan School of Dentistry; 2012.
81. Sarikaya S, Haydar B, Ciger S, Ariyurek M. Changes in alveolar bone thickness due to retraction of anterior teeth. *Am J Orthod Dentofacial Orthop* 2002; **122**: 15–26.
82. Fuhrmann R. Three-dimensional interpretation of periodontal lesions and remodeling during orthodontic treatment. Part III. [In German.] *J Orofac Orthop* 1996; **57**: 224–37.
83. Artun J, Grobety D. Periodontal status of mandibular incisors after pronounced orthodontic advancement during adolescence: a follow-up evaluation. *Am J Orthod Dentofacial Orthop* 2001; **119**: 2–10.
84. Wehrbein H, Bauer W, Diedrich P. Mandibular incisors, alveolar bone, and symphysis after orthodontic treatment. A retrospective study. *Am J Orthod Dentofacial Orthop* 1996; **110**: 239–46.
85. Baysal A, Ucar FI, Buyuk SK, Ozer T, Uysal T. Alveolar bone thickness and lower incisor position in skeletal Class I and Class II malocclusions assessed with cone-beam computed tomography. *Korean J Orthod* 2013; **43**: 134–40. doi: [10.4041/kjod.2013.43.3.134](https://doi.org/10.4041/kjod.2013.43.3.134)
86. Cattaneo PM, Salih RA, Melsen B. Labio-lingual root control of lower anterior teeth and canines obtained by active and passive self-ligating brackets. *Angle Orthod* 2013; **83**: 691–7. doi: [10.2319/071212-575.1](https://doi.org/10.2319/071212-575.1)
87. Marquezan M, Osorio A, Sant'Anna E, Souza MM, Maia L. Does bone mineral density influence the primary stability of dental implants? A systematic review. *Clin Oral Implants Res* 2012; **23**: 767–74. doi: [10.1111/j.1600-0501.2011.02228.x](https://doi.org/10.1111/j.1600-0501.2011.02228.x)
88. Wilmes B, Rademacher C, Olthoff G, Drescher D. Parameters affecting primary stability of orthodontic mini-implants. [In German.] *J Orofac Orthop* 2006; **67**: 162–74.
89. Jung BA, Wehrbein H, Wagner W, Kunkel M. Preoperative diagnostic for palatal implants: is CT or CBCT necessary? *Clin Implant Dent Relat Res* 2012; **14**: 400–5. doi: [10.1111/j.1708-8208.2009.00259.x](https://doi.org/10.1111/j.1708-8208.2009.00259.x)
90. Gracco A, Lombardo L, Cozzani M, Siciliani G. Quantitative cone-beam computed tomography evaluation of palatal bone thickness for orthodontic miniscrew placement. *Am J Orthod Dentofacial Orthop* 2008; **134**: 361–9. doi: [10.1016/j.ajodo.2007.01.027](https://doi.org/10.1016/j.ajodo.2007.01.027)
91. King KS, Lam EW, Faulkner MG, Heo G, Major PW. Vertical bone volume in the paramedian palate of adolescents: a computed tomography study. *Am J Orthod Dentofacial Orthop* 2007; **132**: 783–8.
92. Antonarakis GS, Patel RN, Tompson B. Oral health-related quality of life in non-syndromic cleft lip and/or palate patients: a systematic review. *Community Dent Health* 2013; **30**: 189–95.
93. Leslie EJ, Marazita ML. Genetics of cleft lip and cleft palate. *Am J Med Genet C Semin Med Genet* 2013; **163C**: 246–58. doi: [10.1002/ajmg.c.31381](https://doi.org/10.1002/ajmg.c.31381)
94. Zhou W, Li W, Lin J, Liu D, Xie X, Zhang Z. Tooth lengths of the permanent upper incisors in patients with cleft lip and palate determined with cone beam computed tomography. *Cleft Palate Craniofac J* 2013; **50**: 88–95. doi: [10.1597/11-18](https://doi.org/10.1597/11-18)
95. Oberoi S, Gill P, Chigurupati R, Hoffman WY, Hatcher DC, Vargervik K. Three-dimensional assessment of the eruption path of the canine in individuals with bone-grafted alveolar clefts using cone beam computed tomography. *Cleft Palate Craniofac J* 2010; **47**: 507–12. doi: [10.1597/08-171](https://doi.org/10.1597/08-171)
96. Oberoi S, Chigurupati R, Gill P, Hoffman WY, Vargervik K. Volumetric assessment of secondary alveolar bone grafting using cone beam computed tomography. *Cleft Palate Craniofac J* 2009; **46**: 503–11. doi: [10.1597/08-153.1](https://doi.org/10.1597/08-153.1)
97. Shiota T, Kurabayashi H, Ogura H, Seki K, Maki K, Shintani S. Analysis of bone volume using computer simulation system for secondary bone graft in alveolar cleft. *Int J Oral Maxillofac Surg* 2010; **39**: 904–8. doi: [10.1016/j.ijom.2010.04.050](https://doi.org/10.1016/j.ijom.2010.04.050)
98. Oberoi S, Nervina JM, Vargervik K. 3D imaging in diagnosis and treatment planning of craniofacial anomalies. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 485–508.
99. Hamada Y, Kondoh T, Noguchi K, Iino M, Isono H, Ishii H, et al. Application of limited cone beam computed tomography to clinical assessment of alveolar bone grafting: a preliminary report. *Cleft Palate Craniofac J* 2005; **42**: 128–37.
100. Garib DG, Yatabe MS, Ozawa TO, da Silva Filho OG. Alveolar bone morphology in patients with bilateral complete cleft lip and palate in the mixed dentition: cone beam computed tomography evaluation. *Cleft Palate Craniofac J* 2012; **49**: 208–14. doi: [10.1597/10-198](https://doi.org/10.1597/10-198)
101. Quereshey FA, Barnum G, Demko C, Horan M, Palomo JM, Baur DA, et al. Use of cone beam computed tomography to volumetrically assess alveolar cleft defects—preliminary results. *J Oral Maxillofac Surg* 2012; **70**: 188–91. doi: [10.1016/j.joms.2011.01.027](https://doi.org/10.1016/j.joms.2011.01.027)
102. Zhang W, Shen G, Wang X, Yu H, Fan L. Evaluation of alveolar bone grafting using limited cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012; **113**: 542–8. doi: [10.1016/j.oooo.2011.10.001](https://doi.org/10.1016/j.oooo.2011.10.001)
103. Alexiou K, Stamatakis H, Tsiklakis K. Evaluation of the severity of temporomandibular joint osteoarthritic changes related to age using cone beam computed tomography. *Dentomaxillofac Radiol* 2009; **38**: 141–7. doi: [10.1259/dmfr/59263880](https://doi.org/10.1259/dmfr/59263880)
104. Ahmad M, Hollender L, Anderson Q, Kartha K, Ohrbach R, Truelove EL, et al. Research diagnostic criteria for temporomandibular disorders (RDC/TMD): development of image analysis criteria and examiner reliability for image analysis. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **107**: 844–60. doi: [10.1016/j.tripleo.2009.02.023](https://doi.org/10.1016/j.tripleo.2009.02.023)
105. Ilguy D, Ilguy M, Fisekcioğlu E, Dolekoglu S, Ersan N. Articular eminence inclination, height, and condyle morphology on cone beam computed tomography. *Scientific World J* 2014; **2014**: 761714. doi: [10.1155/2014/761714](https://doi.org/10.1155/2014/761714)
106. Hunter A, Kalathingall S. Diagnostic imaging for temporomandibular disorders and orofacial pain. *Dent Clin North Am* 2013; **57**: 405–18. doi: [10.1016/j.cden.2013.04.008](https://doi.org/10.1016/j.cden.2013.04.008)
107. Honda K, Bjornland T. Image-guided puncture technique for the superior temporomandibular joint space: value of cone beam computed tomography (CBCT). *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2006; **102**: 281–6.
108. Honey OB, Scarfe WC, Hilgers MJ, Klueber K, Silveira AM, Haskell BS, et al. Accuracy of cone-beam computed tomography imaging of the temporomandibular joint: comparisons with panoramic radiology and linear tomography. *Am J Orthod Dentofacial Orthop* 2007; **132**: 429–38.
109. Alkhader M, Ohbayashi N, Tetsumura A, Nakamura S, Okochi K, Momin MA, et al. Diagnostic performance of magnetic resonance imaging for detecting osseous abnormalities of the temporomandibular joint and its correlation with cone beam computed tomography. *Dentomaxillofac Radiol* 2010; **39**: 270–6. doi: [10.1259/dmfr/25151578](https://doi.org/10.1259/dmfr/25151578)
110. Cevidanes LH, Hajati AK, Paniagua B, Lim PF, Walker DG, Falconet G, et al. Quantification of condylar resorption in temporomandibular joint osteoarthritis. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2010; **110**: 110–17. doi: [10.1016/j.tripleo.2010.01.008](https://doi.org/10.1016/j.tripleo.2010.01.008)

111. Shahidi S, Vojdani M, Paknahad M. Correlation between articular eminence steepness measured with cone-beam computed tomography and clinical dysfunction index in patients with temporomandibular joint dysfunction. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013; **116**: 91–7. doi: [10.1016/j.oooo.2013.04.001](https://doi.org/10.1016/j.oooo.2013.04.001)
112. Helenius LM, Hallikainen D, Helenius I, Meurman JH, Kononen M, Leirisalo-Repo M, et al. Clinical and radiographic findings of the temporomandibular joint in patients with various rheumatic diseases. A case-control study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2005; **99**: 455–63.
113. Koyama J, Nishiyama H, Hayashi T. Follow-up study of condylar bony changes using helical computed tomography in patients with temporomandibular disorder. *Dentomaxillofac Radiol* 2007; **36**: 472–7. doi: [10.1259/dmfr/28078357](https://doi.org/10.1259/dmfr/28078357)
114. Yura S, Ooi K, Kadowaki S, Totsuka Y, Inoue N. Magnetic resonance imaging of the temporomandibular joint in patients with skeletal open bite and subjects with no dentofacial abnormalities. *Br J Oral Maxillofac Surg* 2010; **48**: 459–61. doi: [10.1016/j.bjoms.2009.08.009](https://doi.org/10.1016/j.bjoms.2009.08.009)
115. Guyuron B. Facial deformity of juvenile rheumatoid arthritis. *Plast Reconstr Surg* 1988; **81**: 948–51.
116. Nielsen IL. Vertical malocclusions: etiology, development, diagnosis and some aspects of treatment. *Angle Orthod* 1991; **61**: 247–60.
117. Pamporakis P, Nevzatoglu S, Kucukkeles N. Three-dimensional alterations in pharyngeal airway and maxillary sinus volumes in class III maxillary deficiency subjects undergoing orthopedic facemask treatment. *Angle Orthod* 2014; **84**: 701–7. doi: [10.2319/060513-430.1](https://doi.org/10.2319/060513-430.1)
118. Katyal V, Pamula Y, Martin AJ, Daynes CN, Kennedy JD, Sampson WJ. Craniofacial and upper airway morphology in pediatric sleep-disordered breathing: systematic review and meta-analysis. *Am J Orthod Dentofacial Orthop* 2013; **143**: 20–30.e3. doi: [10.1016/j.ajodo.2012.08.021](https://doi.org/10.1016/j.ajodo.2012.08.021)
119. Alsufyani NA, Al-Saleh MA, Major PW. CBCT assessment of upper airway changes and treatment outcomes of obstructive sleep apnoea: a systematic review. *Sleep Breath* 2013; **17**: 911–23. doi: [10.1007/s11325-012-0799-7](https://doi.org/10.1007/s11325-012-0799-7)
120. Han S, Choi YJ, Chung CJ, Kim JY, Kim KH. Long-term pharyngeal airway changes after bionator treatment in adolescents with skeletal class II malocclusions. *Korean J Orthod* 2014; **44**: 13–19. doi: [10.4041/kjod.2014.44.1.13](https://doi.org/10.4041/kjod.2014.44.1.13)
121. Vinoth SK, Thomas AV, Nethravathy R. Cephalometric changes in airway dimensions with twin block therapy in growing class II patients. *J Pharm Bioallied Sci* 2013; **5**: S25–9. doi: [10.4103/0975-7406.113288](https://doi.org/10.4103/0975-7406.113288)
122. Celikoglu M, Bayram M, Sekerci AE, Buyuk SK, Toy E. Comparison of pharyngeal airway volume among different vertical skeletal patterns: a cone-beam computed tomography study. *Angle Orthod* 2014; **84**: 782–7. doi: [10.2319/101013-748.1](https://doi.org/10.2319/101013-748.1)
123. Mattos CT, Cruz CV, da Matta TC, Pereira Lde A, Solon-de-Mello Pde A, Ruellas AC, et al. Reliability of upper airway linear, area, and volumetric measurements in cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2014; **145**: 188–97. doi: [10.1016/j.ajodo.2013.10.013](https://doi.org/10.1016/j.ajodo.2013.10.013)
124. Haskell JA, Haskell BS, Spoon ME, Feng C. The relationship of vertical skeletofacial morphology to oropharyngeal airway shape using cone beam computed tomography: possible implications for airway restriction. *Angle Orthod* 2014; **84**: 548–54. doi: [10.2319/042113-309.1](https://doi.org/10.2319/042113-309.1)
125. Schendel SA, Hatcher D. Automated 3-dimensional airway analysis from cone-beam computed tomography data. *J Oral Maxillofac Surg* 2010; **68**: 696–701. doi: [10.1016/j.joms.2009.07.040](https://doi.org/10.1016/j.joms.2009.07.040)
126. Grauer D, Cevitanes LS, Styner MA, Ackerman JL, Proffit WR. Pharyngeal airway volume and shape from cone-beam computed tomography: relationship to facial morphology. *Am J Orthod Dentofacial Orthop* 2009; **136**: 805–14. doi: [10.1016/j.ajodo.2008.01.020](https://doi.org/10.1016/j.ajodo.2008.01.020)
127. Lenza MG, Lenza MM, Dalstra M, Melsen B, Cattaneo PM. An analysis of different approaches to the assessment of upper airway morphology: a CBCT study. *Orthod Craniofac Res* 2010; **13**: 96–105.
128. Olszewska E, Sieskiewicz A, Rozycki J, Rogalewski M, Tarasow E, Rogowski M, et al. A comparison of cephalometric analysis using radiographs and craniofacial computed tomography in patients with obstructive sleep apnea syndrome: preliminary report. *Eur Arch Otorhinolaryngol* 2009; **266**: 535–42. doi: [10.1007/s00405-008-0826-2](https://doi.org/10.1007/s00405-008-0826-2)
129. Xiao Y, Chen X, Shi H, Yang Y, He L, Dong J, et al. Evaluation of airway obstruction at soft palate level in male patients with obstructive sleep apnea/hypopnea syndrome: dynamic 3-dimensional CT imaging of upper airway. *J Huazhong Univ Sci Technolog Med Sci* 2011; **31**: 413–18. doi: [10.1007/s11596-011-0392-5](https://doi.org/10.1007/s11596-011-0392-5)
130. Yucel A, Unlu M, Haktanir A, Acar M, Fidan F. Evaluation of the upper airway cross-sectional area changes in different degrees of severity of obstructive sleep apnea syndrome: cephalometric and dynamic CT study. *AJNR Am J Neuroradiol* 2005; **26**: 2624–9.
131. Stefanovic N, El H, Chenin DL, Glisic B, Palomo JM. Three-dimensional pharyngeal airway changes in orthodontic patients treated with and without extractions. *Orthod Craniofac Res* 2013; **16**: 87–96. doi: [10.1111/ocr.12009](https://doi.org/10.1111/ocr.12009)
132. El H, Palomo JM. Three-dimensional evaluation of upper airway following rapid maxillary expansion: a CBCT study. *Angle Orthod* 2014; **84**: 265–73. doi: [10.2319/012133-71.1](https://doi.org/10.2319/012133-71.1)
133. Chang Y, Koenig LJ, Pruszyński JE, Bradley TG, Bosio JA, Liu D. Dimensional changes of upper airway after rapid maxillary expansion: a prospective cone-beam computed tomography study. *Am J Orthod Dentofacial Orthop* 2013; **143**: 462–70. doi: [10.1016/j.ajodo.2012.11.019](https://doi.org/10.1016/j.ajodo.2012.11.019)
134. Iwasaki T, Saitoh I, Takemoto Y, Inada E, Kakuno E, Kanomi R, et al. Tongue posture improvement and pharyngeal airway enlargement as secondary effects of rapid maxillary expansion: a cone-beam computed tomography study. *Am J Orthod Dentofacial Orthop* 2013; **143**: 235–45. doi: [10.1016/j.ajodo.2012.09.014](https://doi.org/10.1016/j.ajodo.2012.09.014)
135. Katyal V, Pamula Y, Daynes CN, Martin J, Dreyer CW, Kennedy D, et al. Craniofacial and upper airway morphology in pediatric sleep-disordered breathing and changes in quality of life with rapid maxillary expansion. *Am J Orthod Dentofacial Orthop* 2013; **144**: 860–71. doi: [10.1016/j.ajodo.2013.08.015](https://doi.org/10.1016/j.ajodo.2013.08.015)
136. Hong JS, Park YH, Kim YJ, Hong SM, Oh KM. Three-dimensional changes in pharyngeal airway in skeletal class III patients undergoing orthognathic surgery. *J Oral Maxillofac Surg* 2011; **69**: e401–8. doi: [10.1016/j.joms.2011.02.011](https://doi.org/10.1016/j.joms.2011.02.011)
137. Andrews BT, Lakin GE, Bradley JP, Kawamoto HK Jr. Orthognathic surgery for obstructive sleep apnea: applying the principles to new horizons in craniofacial surgery. *J Craniofac Surg* 2012; **23**: 2028–41. doi: [10.1097/SCS.0b013e31825d05bb](https://doi.org/10.1097/SCS.0b013e31825d05bb)
138. Zeng J, Gao X. A prospective CBCT study of upper airway changes after rapid maxillary expansion. *Int J Pediatr Otorhinolaryngol* 2013; **77**: 1805–10. doi: [10.1016/j.ijporl.2013.07.028](https://doi.org/10.1016/j.ijporl.2013.07.028)
139. Raffaini M, Pisani C. Clinical and cone-beam computed tomography evaluation of the three-dimensional increase in pharyngeal airway space following maxillo-mandibular rotation-advancement for class II-correction in patients without sleep apnoea (OSA). *J Craniomaxillofac Surg* 2013; **41**: 552–7. doi: [10.1016/j.jcms.2012.11.022](https://doi.org/10.1016/j.jcms.2012.11.022)
140. Li YM, Liu JL, Zhao JL, Dai J, Wang L, Chen JW. Morphological changes in the pharyngeal airway of female skeletal class III patients following bimaxillary surgery: a cone beam computed tomography evaluation. *Int J Oral Maxillofac Surg* 2014; **43**: 862–7. doi: [10.1016/j.ijom.2014.03.009](https://doi.org/10.1016/j.ijom.2014.03.009)
141. Burkhard JP, Dietrich AD, Jacobsen C, Roos M, Lubbers HT, Obwegeser JA. Cephalometric and three-dimensional assessment of the posterior airway space and imaging software reliability analysis before and after orthognathic surgery. *J Craniomaxillofac Surg* Apr 2014. Epub ahead of print. doi: [10.1016/j.jcms.2014.04.005](https://doi.org/10.1016/j.jcms.2014.04.005)
142. Habeeb M, Boucher N, Chung CH. Effects of rapid palatal expansion on the sagittal and vertical dimensions of the maxilla: a study on cephalograms derived from cone-beam computed

- tomography. *Am J Orthod Dentofacial Orthop* 2013; **144**: 398–403. doi: [10.1016/j.ajodo.2013.04.012](https://doi.org/10.1016/j.ajodo.2013.04.012)
143. Woller JL, Kim KB, Behrents RG, Buschang PH. An assessment of the maxilla after rapid maxillary expansion using cone beam computed tomography in growing children. *Dental Press J Orthod* 2014; **19**: 26–35.
144. Kanomi R, Deguchi T, Kakuno E, Takano-Yamamoto T, Roberts WE. CBCT of skeletal changes following rapid maxillary expansion to increase arch-length with a development-dependent bonded or banded appliance. *Angle Orthod* 2013; **83**: 851–7. doi: [10.2319/082012-669.1](https://doi.org/10.2319/082012-669.1)
145. Zandi M, Miresmaeili A, Heidari A. Short-term skeletal and dental changes following bone-borne versus tooth-borne surgically assisted rapid maxillary expansion: a randomized clinical trial study. *J Craniomaxillofac Surg* Feb 2014. Epub ahead of print. doi: [10.1016/j.jcms.2014.02.007](https://doi.org/10.1016/j.jcms.2014.02.007)
146. Kartalian A, Gohl E, Adamian M, Enciso R. Cone-beam computerized tomography evaluation of the maxillary dentoskeletal complex after rapid palatal expansion. *Am J Orthod Dentofacial Orthop* 2010; **138**: 486–92. doi: [10.1016/j.ajodo.2008.10.025](https://doi.org/10.1016/j.ajodo.2008.10.025)
147. Kraus CD, Campbell PM, Spears R, Taylor RW, Buschang PH. Bony adaptation after expansion with light-to-moderate continuous forces. *Am J Orthod Dentofacial Orthop* 2014; **145**: 655–66. doi: [10.1016/j.ajodo.2014.01.017](https://doi.org/10.1016/j.ajodo.2014.01.017)
148. Kukemeyer AM. The effects of sutural and cervical vertebral maturation on dentoalveolar versus skeletal responses to rapid maxillary expansion. MSc thesis. University of Michigan School of Dentistry; 2013.
149. Palomo JM, Valiathan M, Hans MG. 3D orthodontic diagnosis and treatment planning. In: Kapila S, ed. *Cone beam computed tomography in orthodontics: indications, insights and innovations*. Hoboken, NJ: Wiley-Blackwell; 2014. pp. 221–46.
150. Hodges RJ, Atchison KA, White SC. Impact of cone-beam computed tomography on orthodontic diagnosis and treatment planning. *Am J Orthod Dentofacial Orthop* 2013; **143**: 665–74. doi: [10.1016/j.ajodo.2012.12.011](https://doi.org/10.1016/j.ajodo.2012.12.011)