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REVIEW ARTICLE

CBCT imaging – A boon to orthodontics

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Abstract The application of innovative technologies in dentistry and orthodontics has been very interesting to observe. The development of cone-beam computed tomography (CBCT) as a preferred imaging procedure for comprehensive orthodontic treatment is of particular interest. The information obtained from CBCT imaging provides several substantial advantages. For example, CBCT imaging provides accurate measurements, improves localization of impacted teeth, provides visualization of airway abnormalities, it identifies and quantifies asymmetry, it can be used to assess periodontal structures, to identify endodontic problems, to plan placement sites for temporary skeletal anchorage devices, and to view condylar positions and temporomandibular joint (TMJ) bony structures according to the practitioner's knowledge at the time of orthodontic diagnosis. Moreover, CBCT imaging involves only a minimal increase in radiation dose relative to combined diagnostic modern digital panoramic and cephalometric imaging. The aim of this article is to provide a comprehensive overview of CBCT imaging, including its technique, advantages, and applications in orthodontics.

Contents

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1. Introduction

As in every other medical and dental specialty, accurate diagnostic imaging is a key factor for an orthodontic diagnosis and treatment planning. In addition, it is an essential tool that allows an orthodontist to closely monitor treatment progress and outcome (Ghoneima et al., 2009). To date, CBCT is more commonly performed for the comprehensive imaging of orthodontic patients than conventional lateral cephalograms and panoramic images. The availability of conventional computerized tomography (CT) scans has also greatly increased the professional demand for three-dimensional (3D) information regarding craniofacial imaging. Cone-beam computed tomography (CBCT) scanners were introduced nearly fifteen years ago as an adaptive technology to meet this demand, while reducing the radiation risks associated with full CT scans. However, in the years following its introduction, a widespread interest in CBCT imaging developed as a result of the varied applications that were demonstrated for this technology in clinical and research fields of study.

2. CBCT

Craniofacial CBCT was designed to offset some of the limitations of conventional CT scanning devices (Halazonetis, 2005) while also reducing the exposure of patients to radiation. A CBCT scan with a single revolution of the radiation source is sufficient to scan the entire maxillofacial region (Sukovic et al., 2001). CBCT technology is based on the use of a cone-shaped X-ray beam that is directed through the patient and the remnant beam is captured on a flat two-dimensional (2D) detector (Fig. 1) (Scarfe et al., 2006). The X-ray source and detector are able to revolve about a patient's head, and a sequence of two-dimensional (2D) images is generated. These 2D images are then converted into a 3D image using computer software. The rapid movement of the X-ray tube and digital detector through 180°, or more frequently through 360°, produces essentially instantaneous and precise 2D and 3D radiographic images of an anatomical structure. Furthermore, these images are only restricted by the system's distinctive, or designated, field-of-view (FOV).

2.1. Advantages of CBCT over conventional CT

1. It is less expensive and involves a smaller system.
2. The X-ray beam is limited.
3. Accurate images are obtained.
4. The scan time is rapid.
5. A lower radiation dose is used.
6. The display modes are exclusive to dentofacial imaging.
7. There are fewer imaging artifacts.

3. CBCT in oral and maxillofacial imaging

In April 2001, NewTom (Quantitative Radiology, Verona, Italy) was the first commercially distributed CBCT system for head and neck imaging. It was sanctioned by the Food and Drug Administration (FDA) and is presently in its fourth generation as the NewTom VG. Subsequently, several other systems have been sanctioned or are in development. These systems can be broadly classified into three groups: (1) CBCT systems capable of imaging a large portion of the maxillofacial and cranial complex with one exposure (large FOV); (2) dedicated CBCT systems with a smaller FOV; and (3) hybrid digital panoramic/CBCT systems which have separate

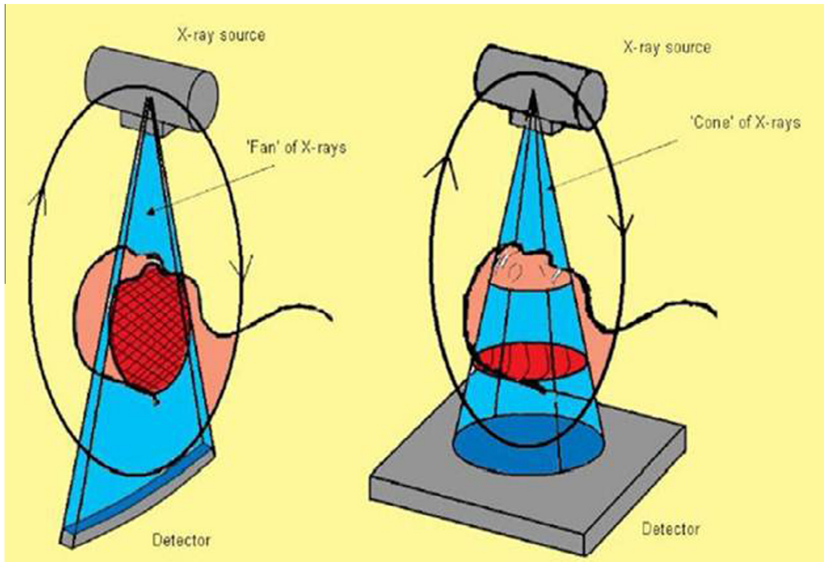

Figure 1 Diagrammatic representation of image capture technique of CT and CBCT devices.

mechanisms for the two functions. Some of the latter systems also provide a 2D digital cephalogram option.

4. Radiation exposure of CBCT

Various reports have described the radiation exposure associated with CBCT scans. In 2003, Mah et al. reported only a 20% reduction in the total radiation dose associated with cone beam CT compared with conventional CT. However, Schulze et al. (2004) subsequently reported that 3D volumetric images obtained with cone beam technology involved up to four times less radiation than conventional CT. Settings such as peak kilovoltage (kVp) and milliampere (mA) are some of the factors which affect the effective radiation dose. The use of lower mAs and/or collimation can reduce the amount of radiation the patient receives, although these settings can also reduce image quality.

The effective exposure dose for a patient from a CBCT machine has been reported to range from 45 microsievert (μSv) to 650 μSv. The reported doses for an analog full mouth series and an analog panoramic radiograph are 150 μSv (Frederiksen, 1995) and 54 μSv (Kiefer et al., 2004), respectively.

5. Orthodontic applications of CBCT

In general, orthodontics has relied on 2D X-rays to assess 3D structures. However, CBCT provides a 3D visualization of the craniofacial skeleton, and this has applications in various orthodontic situations (see Table 1).

6. Application in orthodontic diagnosis

6.1. Assessment of skeletal and dental structures

Conventional cephalometric radiography is limited in its application by the expression of 3D structures onto a 2D plane. As a result, the superimposition of anatomical structures interferes with landmark identification and can lead to magnification and distortion of the image obtained. In contrast, CBCT imaging in association with computer software allows anatomical structures to be properly represented in all three viewing planes – sagittal, coronal, and transverse. Landmark identification is also greatly enhanced in CBCT images with magnification and adjustments in contrast. In 2008, Van Vlijmen et al. stated that the reproducibility of measurements on cephalometric radiographs obtained from CBCT scans was better than that achieved with conventional cephalograms. Multiplanar views are especially advantageous in identifying bilateral landmarks such as condylion, gonion, and orbitale, which are frequently superimposed in conventional radiographs (Ludlow et al., 2009). However, CBCT imaging need not replace conventional radiography, although additional conventional imaging is generally not necessary when CBCT scans are acquired for an orthodontic diagnosis.

6.2. 3D evaluation of impacted teeth

CBCT is commonly used to assess an impacted tooth and its position (Fig. 2). Research has shown that enhanced precision in the localization of canine teeth and improved estimations of the space conditions in the arch can be obtained with CBCT, and this can greatly affect diagnosis and treatment planning to facilitate a more clinically-orientated approach. Small volume CBCT is also justified as a supplement to routine panoramic X-rays in the following cases: when canine inclination in the panoramic X-ray exceeds 30°, when root resorption of adjacent teeth is suspected, and/or when the canine apex is not clearly discernible in the panoramic X-ray, implying dilaceration of the canine root (Wriedt et al., 2012). When comparing conventional radiography and CBCT, Katheria et al. (2010) found that CBCT provides more information regarding the location of pathology, the presence of root resorption, and treatment planning. However, the benefits of CBCT imaging

Table 1 Application of CBCT in orthodontics.

Orthodontic situation	CBCT application
Diagnosis	Assessment of skeletal structures and dental structures • Skeletal jaw relation • Symmetry/asymmetry 3D evaluation of impacted tooth position and anatomys Growth assessment Pharyngeal airway analysis Assessment of the TMJ complex in three dimensions Cleft palate assessment
Treatment planning	Orthognathic surgery treatment planning in true 1:1 imaging Planning for placement of temporary anchorage devices (TADs) Accurate estimation to space requirement for unerupted/ impacted teeth Used in association with CAD/ CAM technology for construction of custom appliances. (Lingual orthodontic appliance)
Treatment progress	Assessment of dentofacial orthopedics Outcomes of alveolar bone grafts in cleft palate cases Orthognathic Surgery superimposition
Risk assessment	Investigation of orthodontic-associated paraesthesia Assessment of orthodontics induced root resorption Post treatment TMD

must be weighed against the radiation risk to pediatric patients and the complexity of the pathology involved.

6.3. Growth assessment

CBCT scans can be used to reliably assess cervical vertebrae maturity, which provides a consistent evaluation of skeletal maturity (Joshi et al., 2012).

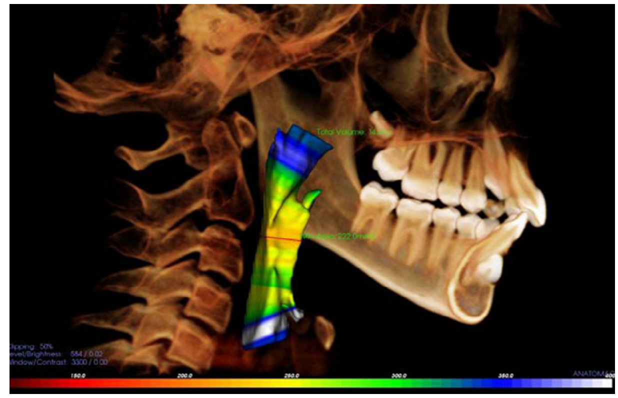

Figure 3 CBCT image for airway analysis.

6.4. Pharyngeal airway analysis

Lateral cephalograms have been routinely used to assess the airway using techniques involving both tissue and soft tissue points. Conventional radiography and reconstructed 2D CBCT images provide similar assessments of the airway. In comparison, axial cuts of 3D CBCT scans (Fig. 3) provide soft tissue points that are derived from the projection of shaded areas, which are more clearly visible in axial CBCT cuts compared with conventional radiographs, thereby enhancing airway assessment (Vizzotto et al., 2012). Three-dimensional CBCT-assisted airway analysis also facilitates the diagnosis and treatment planning of complex anomalies including enlarged adenoids and obstructive sleep apnea (OSA). In 2007, Ogawa et al. investigated airway morphology in OSA-affected patients. The apnea-affected subjects showed a significant decrease in airway volume, area, and distance, thereby highlighting the importance of CBCT in the diagnosis of this condition.

6.5. Assessment of the temporomandibular joint (TMJ) complex in three dimensions

Honey et al. (2007) compared CBCT imaging of the TMJ complex with panoramic radiography and linear tomographic views, and found that the CBCT images (Fig. 4) were more accurate and showed superior reliability in diagnosing condylar morphology disturbances and erosion. For a complete bilateral TMJ exam, an average of four tomographic cuts in both the lateral and frontal planes are needed for each TMJ.

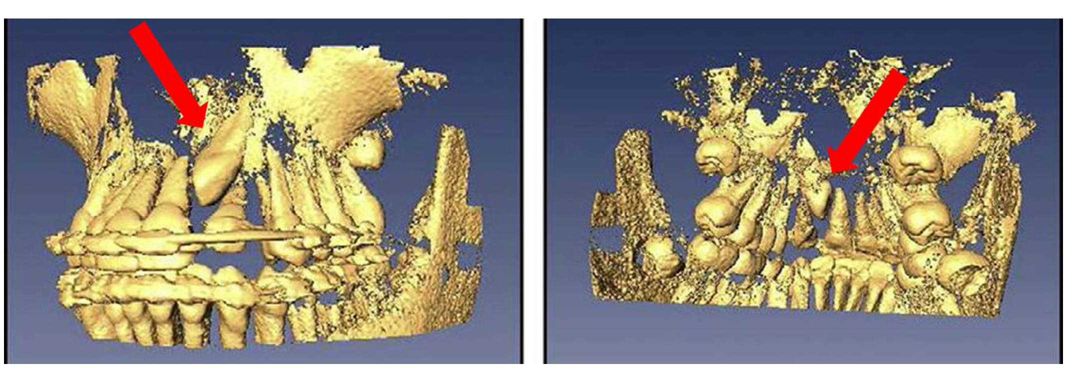

Figure 2 CBCT image of impacted upper left canine.

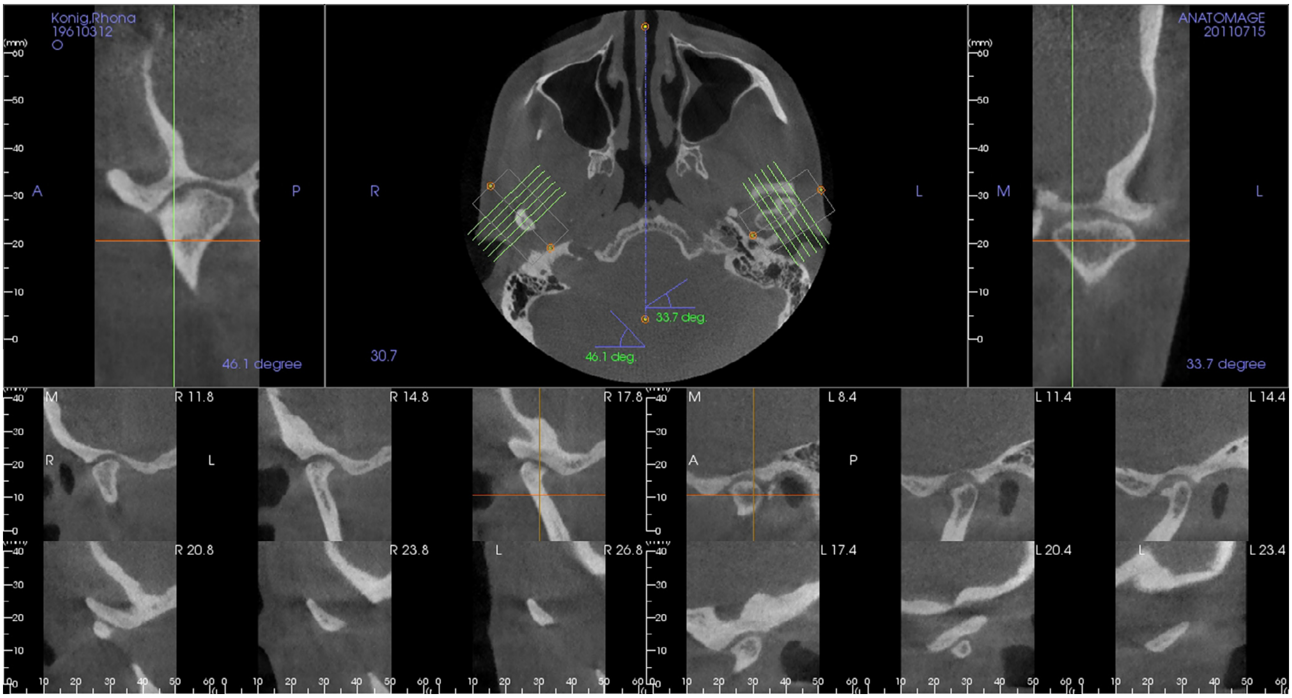

Figure 4 CBCT image showing assessment of condylar anatomy.

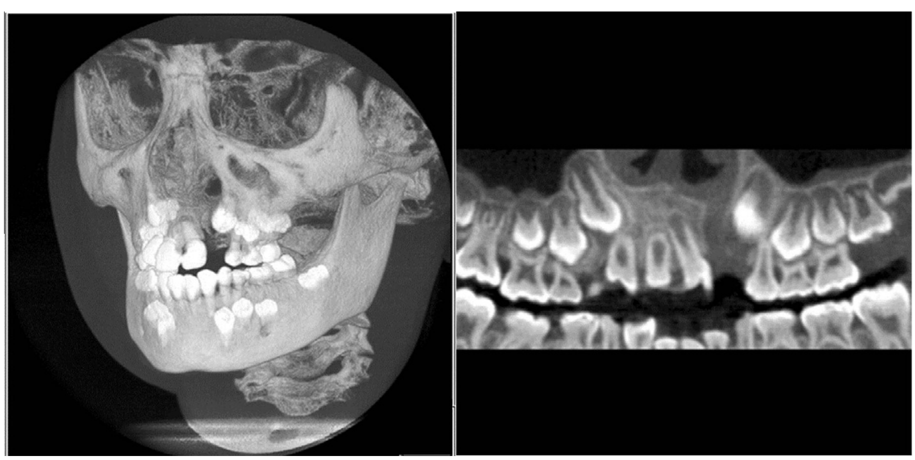

Figure 5 CBCT image of a patient with unilateral cleft palate.

In addition, scout images preceding the actual tomography are needed. In comparison, a CBCT examination requires less time, it includes image data for both the right and left TMJs from a single 360° rotation scan around the patient's head, and it simplifies patient positioning. Additional advantages include a potentially lower radiation dose and the possibility of multiplanar views and image manipulation in the form of rotated views (Hintze et al., 2007). When validating the use of CBCT for TMJ analysis, the clinician should deliberate whether the information acquired will affect the management of the patient. Findings such as hard tissue erosions, remodeling, or the presence of any structural deformities may be absolutely documentary and may have no bearing on treatment protocol. In general, CBCT is not the imaging of choice for TMJ disorders such as myofacial pain dysfunction or internal disk derangements.

6.6. Cleft palate assessment

CBCT for patients with cleft lip and palate (Fig. 5) is useful for both preoperative and therapeutic evaluations. The real-time creation of images in several planes and parasagittal sections through the imaging volume has broad applications in the assessment of cleft palate cases. Three-dimensional reconstructions of images in association with 3D navigation systems allow preoperative evaluations of the cleft palate regarding the volume of the bone defect, the location of the bone defect, the presence of supernumerary teeth, and an appraisal of permanent

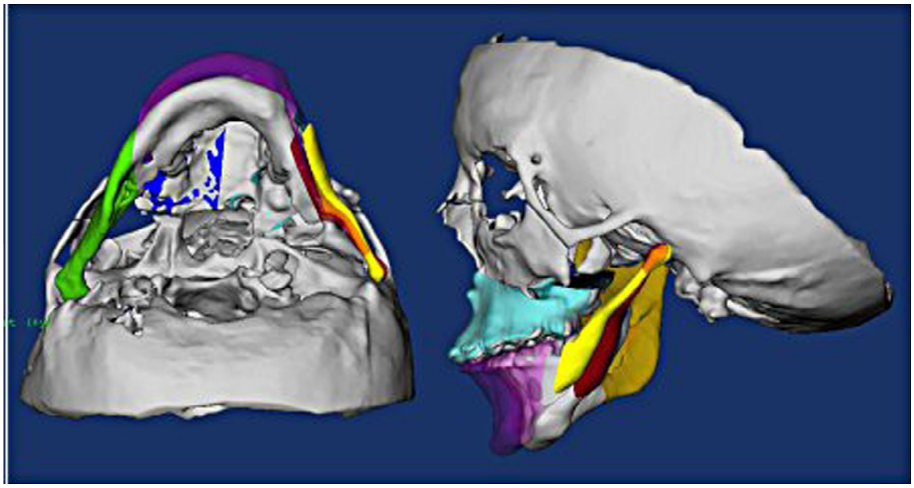

Figure 6 Surgical simulation to plan displacement of colored segments.

teeth and alveolar bone morphology (Schneiderman et al., 2009). In a study by Albuquerque et al. (2011), CBCT was found to be equivalent to multi-slice CT in both the volumetric assessment of bone defects in alveolar and palatal regions and in establishing donor area and the volume of the bone graft to be used in the rehabilitation of cleft patients.

7. Applications of CBCT in treatment planning

7.1. Orthognathic surgical planning

CBCT imaging in tandem with appropriate software and virtual patent-specific models enables the examination of hard and soft craniofacial tissues and their spatial relationships. Virtual anatomical models can be fabricated from CT volumes and co-registered with other available 3D image data. Thus, the virtual models that are generated can be used to recreate or check treatment options, to create anatomically correct substitute grafts, and can be a critical aid during the surgical procedure. In addition, databases may be interfaced with the anatomical models to provide characteristics of the displayed tissues to reproduce tissue reactions to development, treatment, and function. For example, maxillofacial soft tissues can be ascribed with viscoelastic properties and can be associated with related hard tissues so that replicated manipulation of the hard tissues (e.g., teeth and skeleton) (Fig. 6) produces a correct deformation reaction in the attached soft tissues. This method can offer a more distinct depiction of anticipated changes subsequent to surgical treatment compared with less sophisticated computer modeling (Schendel et al., 2009).

7.2. Planning for placement of temporary anchorage devices (TADs)

The placement of TADs can greatly enhance the information derived from CBCT imaging (Fig. 7). Three-dimensional scans are especially useful in evaluating the amount and quality of bone available in the desired site of placement (Kim et al., 2009). Therefore, with this single diagnostic imaging method, information about surrounding structures, root proximity, and the morphology of maxillary sinuses and the inferior alveolar nerve canal can be obtained, all of which are important in determining TAD stability and success. Surgical guides that have been developed using a method employing high resolution CBCT scans and rapid prototyping have been shown to provide accurate placement of TADs on the buccal aspect of the jaws (Kim et al., 2007). Three-dimensional CBCT image-based stereo lithographic surgical stent guides (Qiu et al., 2012) have also been found to be more accurate than 2D surgical guides in micro implant placement.

7.3. Accurate estimation of the space requirement for unerupted/impacted teeth

CBCT scans enable the accurate localization of impacted and/or transposed teeth, and this helps determine the best method for surgical access and bond placement. It also helps delineate the ideal and most efficient path for extrusion into the oral cavity to circumvent or decrease collateral damage. Furthermore, CBCT scans provide the orthodontist with valuable information regarding the teeth neighboring the impacted teeth in

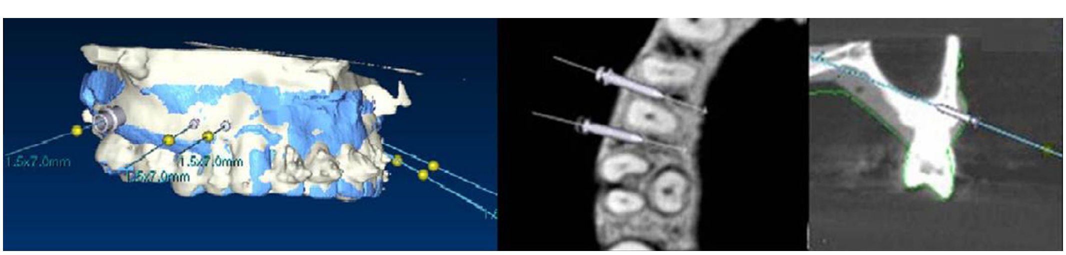

Figure 7 Planning of TAD placement.

terms of root proximity. This information can then be used to place adjacent teeth and their roots away from the traction path of the impacted tooth so as to avoid untoward changes in these teeth. Another advantage of CBCT over conventional radiographs is its capacity to obtain precise dimensions of an impacted tooth, which aids in estimating and creating the necessary space to accommodate the tooth within the arch.

7.4. Fabrication of custom orthodontic appliances

The fabrication of custom lingual orthodontic appliances has been demonstrated using CBCT image data with existing technology to virtually plan a patient's treatment and the manufacturing of custom appliances with 3D printing technology (Ye et al., 2011). Such advances appear to be rapid, and they also promise efficient and effective patient-specific treatments. Correspondingly, Orametrix (Richardson, TX) is a company that has been using CBCT technology for the last several years to provide the data necessary for planning and executing technology-assisted treatment through its SureSmile system (Larson, 2012).

8. Application of CBCT in assessing treatment progress and outcome

8.1. Dentofacial orthopedics

Cevidanes et al. (2009) previously investigated the possibility of using CBCT scans for evaluating treatment outcomes for Class III growing patients that were treated with maxillary protraction using Class III inter-arch elastics attached to mini-plates. They found that 3D overlays of superimposed models and 3D color coded displacement maps provided visual and quantitative assessments of growth and treatment changes. CBCT scans were able to identify maxillary and mandibular positional changes and bone remodeling relative to the anterior cranial fossa. Rapid maxillary expansion treatment outcomes have also been evaluated using CBCT images and scans. Overlapping of anatomical structures is able to be circumvented using 3D scans, and hence, skeletal and dental changes can more accurately be evaluated (Garrett et al., 2008). However, there is a need for more research and a definitive analysis regarding the standardization of superimposition

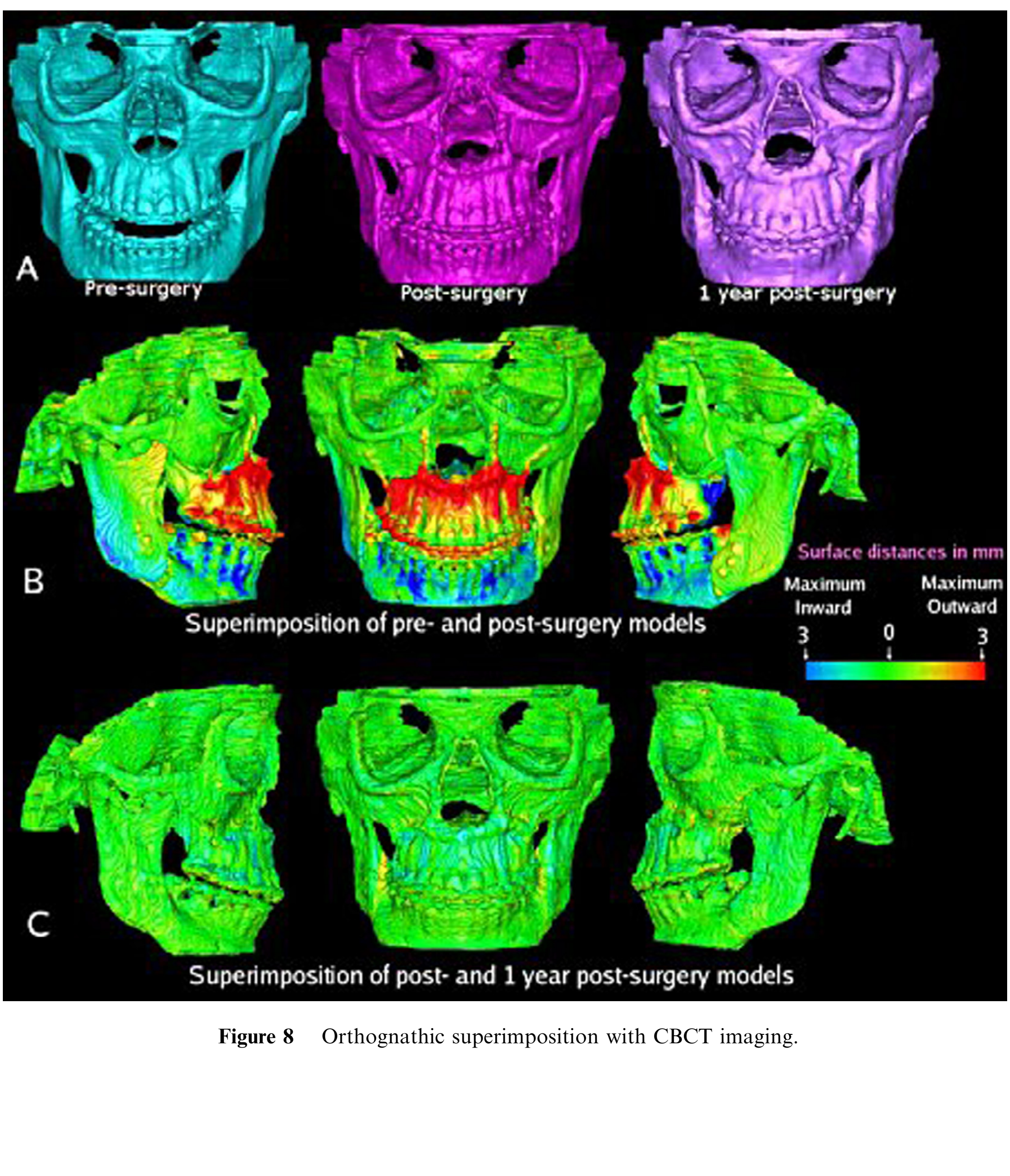

Figure 8 Orthognathic superimposition with CBCT imaging.

areas in 3D scans since the superimposition of 3D surface models is currently a time consuming and operator sensitive process (Cevidanes et al., 2010).

8.2. Orthognathic surgery superimposition

Studies of surgical treatment outcome may be facilitated by using a new superimposition method (Fig. 8) which enables the operator to superimpose a custom surface mesh of the first CBCT image onto a second CBCT image of the anterior cranial base.

In 2009, Swennen et al. recommended the following three-stage sequence for imaging when evaluating surgical treatment outcomes using CBCT:

1. Stage 1 (3–6 weeks post-operatively): imaging is used to verify the transfer of bony parts. This time frame circumvents post-operative soft tissue swelling which might interfere in occlusion and is prior to bony consolidation, thereby providing proper visualization of osteotomy lines.
2. Stage 2 (6 months to 1 year post-operatively: imaging at this stage evaluates the soft tissue response and should preferably occur after the removal of orthodontic brackets.
3. Stage 3 (2 years or more post-operatively): this imaging is used to evaluate long-term changes in surgical treatment.

Almeida et al. (2011) used CBCT volume-derived virtual facial models to evaluate post-surgical changes in the soft tissue overlying the mandible in response to mandibular advancement surgery. They superimposed the virtual models at the cranial base and used color maps to qualitatively evaluate surgical and postsurgical changes. A comparison of color maps derived from CBCT images and corresponding computer software analysis was also reported by Cevidanes et al. (2005).

9. Application of CBCT in risk assessment

9.1. Investigation of orthodontic-associated sensory disturbances

Sensory disturbances of the lower lip and chin area are commonly reported after orthognathic surgery, after dentoalveolar surgery following endodontic treatment, or following removal of the mandibular third molars. In contrast, reports of sensory disturbances occurring secondary to regular orthodontic treatment are extremely rare. However, when they do occur, they can only be diagnosed by CBCT. These neural disturbances that occur during orthodontic treatment are classified as neuropraxias and they usually result from temporary conduction blockade due to compression of the inferior alveolar nerve bundle. The duration of the effects that patients experience may range from a few hours to several months, and usually, complete sensory recovery is achieved. A report by Chana et al. (2013) of orthodontic treatment-induced transient mental nerve paresthesia demonstrated the importance of CBCT scans as the sole aid in obtaining a definitive diagnosis of this clinical condition.

9.2. Assessment of orthodontics-induced root resorption and periodontal tissues

CBCT can potentially provide improved visualization of roots, thereby making it a valuable method for evaluating pre-orthodontic or post-orthodontic root resorption. Moreover, CBCT has been found to be comparable to periapical radiography for surveys of root and tooth length (Sherrard et al., 2010). CBCT is also a good method for assessing alveolar bone height, yet is associated with a high number of false-positives in the detection of fenestrations. Thus, caution must be used when gauging these types of defects on CBCT images. Misch et al. (2006) reported that CBCT imaging provides a significant advantage over conventional radiographs for periodontal assessment since it allows buccal and lingual defects to be measured, as well as interproximal defects. Other investigators have also found that CBCT-derived images offer advantages for periodontal assessment. For example, Dudic et al. (2009) compared the efficacy of orthopantograms versus high-resolution CBCT scans in evaluating and estimating apical root resorption secondary to orthodontic treatment. They found that the CBCT scans were useful diagnostic tools for making a decision whether orthodontic treatment should be continued or modified when orthodontic-induced root resorption is detected.

9.3. Post treatment TMD

By providing concurrent visualization of TMJs and maxillo-mandibular spatial relationships and occlusion, CBCT images provide clinicians with the opportunity to visualize and measure the local and regional effects associated with TMJ abnormalities. Similarly, cases involving centric occlusion versus centric relation (CO/CR) discrepancies, unilateral Class II malocclusions, or a retrognathic mandible may involve displacement of the TMJ in CO versus CR, and additional diagnostic information derived from CBCT scans would be beneficial in these cases (Ferreira et al., 2009).

9.4. Supplementary findings, overlooked findings, and medico-legal implications

The frequency of supplementary findings detected in CBCT images, aside from the primary goal of the scans, has been reported to be as high as 25% (Cha et al., 2007). These findings have involved the airway, nasal polyps, TMJ aberrations, sinus pathologies, cervical vertebrae clefts, and endodontic lesions. An additional query that requires further investigation is the capacity of the orthodontist to recognize non-orthodontically related findings and to make suitable recommendations and referrals when required. A lack of identification of accompanying lesions can have significant medico-legal implications. On the other hand, the possibility of establishing a diagnosis based on false-positive findings by the untrained eye has the potential to cause unnecessary distress to the patient and their family, while also increasing the costs of healthcare. The relatively high frequency of incidental findings on CBCT scans (25%) suggests that CBCT scans obtained for orthodontic purposes should be further reviewed by an oral maxillofacial radiologist (Kapila et al., 2011). Orthodontists would also greatly benefit from additional training in identifying typical and atypical anatomy in CBCT images, and this in turn, could provide further identification of components conclusive to their diagnosis.

10. Conclusion

The contributions of CBCT to the field of dentistry have been demonstrated in several studies of technology appraisal, in craniofacial morphology as it relates to health and disease, and in the usefulness of CBCT images for diagnosis, treatment planning, and treatment outcome. Accumulating evidence continues to demonstrate that CBCT is a valuable tool, and it is particularly important in cases where conventional radiography cannot provide adequate diagnostic information. The latter includes cases of cleft palate, craniofacial syndromes, supernumerary teeth, assessment of multiple impacted teeth, identification of root resorption caused by impacted teeth, and planning for orthognathic surgery. CBCT imaging may also be applied to other types of cases in which it is likely to provide valuable diagnostic information following verification of a positive benefit.

Conflict of interest

The authors have no conflicts of interest to report.

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