REVIEW

Cone Beam Computed Tomography in Orthodontics

İpek Coşkun[1] (ID), Burçak Kaya[2] (ID)

[1]Private Practice, İstanbul, Turkey
[2]Department of Orthodontics, Başkent University School of Dentistry, Ankara, Turkey

ORCID IDs of the authors: İ.C. 0000-0002-7515-6160; B.K. 0000-0002-7953-3445.

ABSTRACT

Orthodontists treat malocclusions by applying three-dimensional forces. For years, the diagnosis of this three-dimensional condition and the related treatment plan has been based on two-dimensional imaging. Lateral and anteroposterior cephalometric, panoramic, and periapical radiographs are some of the two-dimensional radiographs routinely used in orthodontics. Despite being highly beneficial in evaluating skeletal and dental relations, these radiographs fail to provide sufficient two-dimensional information in certain cases. The purpose of this compilation is to review the use of cone-beam computed tomography in orthodontics.

Keywords: Cone-beam computed tomography, lateral cephalometry, anteroposterior cephalometry

CONVENTIONAL COMPUTED TOMOGRAPHY

Computed tomography (CT) was developed by Sir Godfrey Hounsfield in 1967. Six generations of these systems have been developed since 1967. The system classification is based on the pieces of the devices and the physical movements of the X-ray. There was a single radiation source and a detector in the first-generation tomographies. An image was taken in sections. In the second-generation tomographies, there were a number of detectors. However, these detectors were unable to display the entire object. In the third generation, on the other hand, great improvements were provided in the detectors and data gathering technology. The large detectors reduced the requirement of a radiation source to move around the object and were called "fan beam CT." However, ring shaped artefacts and distortions usually occur on the generated images. Fourth-generation tomographies were developed to address this issue. A moving radiation source and a fixed detector were created. This indicated considering modifications in the angle of the radiation source; hence, there was a more reflected radiation. Finally, fifth and sixth generation tomographies were developed to diminish the movement and reflection artefacts. In both the generations, the detector is fixed and the electron ray scans the semicircular tungsten strip anode. Radiation is generated at the point where the electron ray hits the anode and is transmitted to the object through a rotating X-ray source (1).

Conventional computed tomographies have certain restrictions. Owing to very large size, tomography machines require huge physical spaces where they are located. They are much more expensive than conventional radiography machines. Images are made of a number of sections, and it consumes immense time and money to obtain a final image. The main reason restricting the use of CT in orthodontics is however the high dose of radiation (1).

CONE-BEAM CT

CBCT Technique
Cone-beam CT (CBCT) was introduced in the market with an aim to bring a solution to the disadvantages of con-

ventional CT in Europe in 1998 (NewTom QR-DVT 9000, Quantitative Radiology Srl, Verona, Italy) and in the USA in 2001 (2).

During a CBCT scanning, the X-ray source and sensor usually revolve 360 degrees on an orbit around the object. A number of images (approximately 150-599) are obtained during the scan. The scan time varies as 5-40 s depending on the CBCT unit and protocol configurations. The size of the ray radiated by the X-ray source is restricted by a round or rectangle collimator. The ray is restricted by the collimator in conformity with the sensor size, but in certain cases, it can be restricted depending on the size of the region of interest. Following the scan, raw data are transformed into voxels and digitally stored in computers (digital volumes). These volumes are then transformed into a format that can be monitored using special software. Voxels are the smallest sub units of a digital volume. CBCT voxels are generally isotropic, i.e., they have equal sizes in all three dimensions of space. The size of the edges comprising the voxels varies between 0.07 and 0.4 mm. Each voxel absorbs a certain amount of X-ray and corresponds to a gray-scale value (3). Last generation CBCT units generate 12- or 14-bit images (12 bit=2^{12}=4096 gray tone, 14 bit=2^{14}=16.384 gray tone). The computer monitors used to display 12- or 14-bit images have a maximum 8-bit (256 gray tone) display capacity. A technique called "windowing and leveling" is used to display the entire image in the software. Windowing allows moving the data in a three-dimensional way so that low-density air and soft tissue and high-density bones and teeth are displayed as 8 bit at once. When optimal windowing level is provided, contrast and brightness (leveling) of the image is configured by the clinician to provide the best display. A higher number of voxels and a higher bit value are associated with a better display of the anatomic structures (2, 4, 5).

The imaging protocol varies depending on the field of view (FOV), voxel size, scan time, milliampere and kilovolt settings, sensor sensitivity, and patient immobilization methods. FOV can be small, medium, or large scale. In small scale FOV, impacted teeth, root morphology, supernumerary teeth, and areas of implants or orthodontic mini implants can be viewed. In medium scale FOV, the mandible, maxilla, or both can be evaluated. In large scale FOV, the entire head area can be evaluated. The operator can control FOV, milliampere settings, and scan time. Diminishing these values decreases the effective radiation, but the image quality scales down accordingly (2).

The voxel volume can be viewed using different imaging options. Imaging options can be in multiplanar (MPR) or orthogonal (i.e., coronal, axial, and sagittal) angles. The obtained data can be sorted as a single voxel line or column. The displayed voxel layers are used to form a larger unit. Thus, clinicians can provide a whole image and display it from the desired angle. Different techniques, such as shaded surface display (SSD) and volume rendering (VR) can be used to display voxel volume by using the aforementioned imaging options (2).

SSD allows displaying the data with a certain density value. While displaying soft tissues, a low-density range is selected and tissues outside this range (hard tissues) are not displayed. While

displaying hard tissues, a high-density range is selected and tissues outside this range (soft tissues) are not displayed. VR is a technique that can use all the voxels but does not allow the operator to change the translucency value using the density level. When superficial soft tissues are made pellucid by 70%, the underlying skeletal structure becomes visible (2). For example, the Hounsfield unit of air is -1000, and the Hounsfield unit increases as the density of the tissues increases. By considering the fact that the Hounsfield unit of all soft and hard tissues in the human body is higher than air and by changing the threshold settings of the CBCT unit, it is possible to provide a clearer view of the tissues.

Every CBCT system has its own software. However, if the data collected by the CBCT software is stored in the Digital Imaging and Communications in Medicine (DICOM) format, the obtained data can be viewed in other CBCT software. Therefore, an interactive imaging system can be created and diagnosis and treatment plans can be developed (6).

With regard to radiation calculation in CBCT, dose applications are generally performed in a dosimetry phantom: a skull placed in a material equivalent to the soft tissue in radiologic terms. Phantoms are divided into several layers throughout the axial plan. Non-calibrated thermoluminesence dosimetries (TLDs) are located in radiosensitive regions in the phantom; these radiosensitive regions are the ramus, thyroid gland, salivary gland, bone marrow, esophagus, brain, and right and left eye. The radiation dose is calculated via these TLDs. The CBCT system obtains images of the phantoms by changing FOV, scan time, milliampere setting, and voxel size every time. The dose absorbed by TLD is calculated depending on the 1990 or 2007 International Commission on Radiological Protection tissue weight factors to detect the effective dose (2, 7). Radiographical imaging should be executed if the expected benefits would outweigh the concerned risks as per the As Low as Reasonably Achievable principle (8). A study ascertained that 87-206 microsievert (µSv) radiation is taken up by CBCT; 14.2-24.3 µSv by panoramic radiography; 10.4 µSv by lateral cephalometry; and 13-100 µSv with full mouth periapical radiography (9). Another study found out that 139 µSv radiation is utilized during a round trip between Paris and Tokyo (10). However, the ionizing feature of the radiation uptaken during the flight is much lower when compared to a CT. As devices conveying direct X-rays emit ionizing radiation, they have more dangerous effects on tissues and cells. In CTs, the dose was reduced from 6000 to 2600 µSv (11). It is not possible for any CBCT system equipped with the highest milliampere and kilovolt setting and with the highest image quality to even achieve these values (1). Thus, it is far more reasonable to prefer CBCT than CT.

The CBCT systems available in the market are different from each other in terms of the patient position during imaging (lying, standing, or sitting), sensor type, FOV, X-ray source, and imaging software (12).

CBCT Systems with Large FOV
These are used to evaluate the entire head-neck area. Currently,

there are 12 different brands of these devices in the market with the FOV size varying between 16×18 and 19×24 cm, and the voxel size varying between 0.08 and 0.20 mm (1, 13).

CBCT Systems with Medium FOV

These are used to evaluate the mandible, maxilla, or both. Currently, there are 19 different brands of these devices in the market whose FOV size varies between 7×12 and 14×24 cm, and the voxel size varies between 0.07 and 0.40 mm (13).

CBCT Systems with Small FOV

These are used to evaluate impacted teeth, root morphology, supernumerary teeth, and areas of implants or orthodontic mini implants. Till date, there are 25 different brands of these devices in the market whose FOV size varies between 3×4 cm 10×10 cm, and the voxel size varies between 0.07 and 0.20 mm (1, 13).

Advantages of CBCT (14)

- Three-dimensional display,
- Real-size data,
- Optional two-dimensional display (posteroanterior cephalogram, lateral cephalogram, TME imaging, and panoramic radiography),
- Isotropic voxel size,
- High resolution image,
- Radiation dose lower than CT. It has been proved that the CBCT radiation dose is lower than that of CT by up to 98%. A study obtained 44 μSv as the highest effective dose for the Accuitomo system and 26.6 for the Scanora system with medium FOV in a high resolution mode. These values are 2-4 times the panoramic radiography with an effective dose of 4.7-14.9 μSv (3),
- Probability of metal artefact is much lower than CT,
- Much cheaper than CT,
- Magnification, distortion, superimposition of structures, and rational errors in two-dimensional imaging are eliminated (15, 16),
- Easy access and use,
- Easy use at clinics,
- Compatible with DICOM files,
- Consumes less energy than CT.

Disadvantages of CBCT (14)

- Low contrast range depending on the detector type,
- Restricted detector size causes restricted FOV and scanned area,
- Although CBCT can view hard tissues and most soft tissues, it cannot display muscles and connections (1),
- Involuntary muscle movements, such as breathing during the long scan (30-40 s), results in movement artefact. For this reason, the patient should remain motionless. It is recommended that patients do not breathe and keep their eyes closed (1).

USE OF THE CBCT IN ORTHODONTICS

A study on CBCTs conducted between May 2004 and January 2006 showed that 51% of them required maxillofacial surgery specialists and 17% required periodontology specialists; 40% of CBCTs were required for implant planning, 24% for a suspected pathology, and 16% for a TME analysis. Apart from these, CBCTs were needed the most for the evaluation of the impacted teeth and for orthodontic evaluations (17). However, it should be considered that if conventional radiographies do not provide enough diagnostic information, CBCT should be performed.

Evaluation of Impacted Teeth and Oral Anomalies

Studies found the impacted maxillary canine prevalence to be 0.9%-6% (18, 19). The ratio of palatal impaction to labial impaction can be as high as 9:1 (20). The traditionally used method in the detection of impacted teeth is the tube shift (parallactic technique) method. In this technique, two periapical radiographies are taken with different ray angles, and it is determined whether the impacted tooth is labial or palatal to the roots of the incisors (21). Apart from the parallactic technique, panoramic radiography and/or panoramic radiography along with lateral cephalometric radiography can be used (22, 23). However, in CT operations, it was found that the positions of the impacted teeth and pathologies they caused were much different from the aforementioned techniques (24). In a study executed using CT, Ericson and Kurol researched about the incisor resorption due to ectopic maxillary canines and observed resorption in 3% of the lateral incisors and in 9% of the central incisors (25). However, in a study by Walker and colleagues executed using CBCT, resorption in 66.7% of the lateral incisors and in 11.1% of the central incisors were detected (26). Absolute localization of impacted teeth with the use of CBCT allows determining the existence of resorption in the neighboring roots, the type of resorption, the root with resorption in multiple root teeth, the amount of the bone surrounding the impacted tooth, the development phase of the tooth, the treatment with minimal invasive surgery, and the most effective orthodontic treatment. A study was conducted on the effects of CBCT on decisions of orthodontists for treatment of impacted teeth with panoramic, occlusal, and parallactic techniques (27). About one-fourth of the treatment plans with two-dimensional radiographies was subjected to change when CBCT was reviewed (e.g., pulling a lateral tooth with a resorbed root instead of pulling a premolar tooth for the eruption of the impacted tooth). Orthodontists could provide a more reliable diagnosis with CBCT than that with the two-dimensional radiograph.

With CBCT, it is possible to detect anomalies, such as oral cysts, supernumerary teeth, enostosis, condensing osteitis, dense bone islands, and osteopetrosis. An absolute localization of supernumerary teeth can be provided, and the clinician can decide which tooth or teeth to extract and the proper surgical approach to achieve it (28). Tooth movement can be extremely hard and gap filling or torque control may not be possible in patients with lesions such as dense bone islands and enostosis. If the force applied to the tooth is in direct position to this dense lesion, external apical root resorption may occur (8).

Deep bite is another frequently observed condition in patients in orthodontics. The intrusion of the anterior teeth and extrusion of the posterior teeth is possible in these patients by using ante-

rior bite planes. The bone in the apical portion of the maxillary central teeth can be evaluated by a cross section from the incisor area with CBCT. Intrusion should not be executed on these teeth if there is insufficient bone because it can cause harm to the tooth apex if a counter force is applied to the dense bone of the bottom of the nose. Therefore, it is necessary to provide extrusion of the posterior teeth during treatment (8).

Evaluation of the Airway and Sinus

Mouth breathing and airway obstructions are some of the malocclusion etiologies. Therefore, evaluation of the airway and the sinus constitutes great importance in orthodontic terms. This evaluation is traditionally performed by lateral cephalometric radiography. However, operations with this radiography are generally insufficient due to small number of examples, lack of control group, lack of standardization in head position of patients, and weak operation designs (29). In the end, it is impossible to get efficient anatomic measurements from lateral cephalometric radiographies (8). A study executed on 11 samples using lateral cephalometric radiography and CBCT showed that different results were obtained by the two radiography techniques for the measurement of the upper airway area and volume (30). It is possible to display the upper airway, soft palate, and tongue and hypopharyngeal structures with CBCT, and more healthy results are obtained compared with the two-dimensional analyses (12). These three-dimensional analyses would be very beneficial in comprehending the effects of obstructive sleep apnea and adenoids on malocclusions and planning proper treatment (1).

El and Palomo (31) in their upper airway volume measurements compared three DICOM viewers [Dolphin3D (version 11, Dolphin Imaging & Management Solutions, Chatsworth, CA), InVivoDental (version 4.0.70, Anatomage, San Jose, CA), and OnDemand3D (version 1.0.1.8407, CyberMed, Seoul, Korea)] with a program of which accuracy was previously tests named OrthoSegment (OS; Developed by Department of Orthodontics at Case Western Reserve University, Cleveland, Ohio) in terms of reliability and accuracy. Thirty CBCT scans were randomly selected and the volume of the oropharynx and the nasal passage area was measured. Reliability was found to be high for all programs. The highest correlation for the oropharynx volume was between Dolphin3D and OS and for the nasal passage volume between InVivoDental and OS. The three DICOM programs were found highly reliable in airway volume measurements, but they showed weak accuracy due to systematic errors.

In another study, El and Palomo (32) researched whether nasal passage and oropharyngeal airway measurements varied between patients with different skeletal patterns. The oropharyngeal volume was found to be smaller in Class II patients compared to Class I and Class III patients. According to the skull base, the position of the mandible had an effect on the oropharyngeal airway volume. Nasal passage volume is lower in Class II patients than in Class I.

Kim et al. (33) compared three-dimensional pharyngeal airway volume in 27 children with retrognathic mandibles and normal craniofacial growth. The total airway volume was found to be smaller in retrognathic individuals than those with normal anteroposterior skeletal relation.

Iwasaki et al. (34) studied the characteristic shape of the oropharyngeal airway in children with Class III malocclusion and found a larger and flatter airway compared to Class I malocclusion.

Evaluation of the Alveolar Bone Height and Volume

CT scans were used especially by implantology specialists to evaluate the alveolar bone size and quality. However, the use of CBCT has increased because of reduced cost and radiation dose (35). Bone volume, quality, roots of the neighboring teeth, and localization of neighboring anatomic structures are important for mini-screw placement in orthodontics. It was reported that CBCT images provided more accurate and reliable information in viewing inter-radicular relations compared to panoramic radiography (36). Thus, both accurate placement of orthodontic mini screws and application of proper force vectors for these screws can be provided (21). Besides, surgical guidelines can be created for placement of orthodontic mini screws by using high-definition CBCT scans (37). However, it should be considered that although CBCT provides accurate information for evaluating the alveolar bone height, it gives substantial errors in the evaluation of fenestration and dehiscence. Therefore, caution should be maintained while evaluating such defects (38, 39).

TMJ Evaluation

Temporomandibular joint (TMJ) changes that occur as a result of orthognathic surgery, distraction osteogenesis, and orthopedic treatments require detailed studies. As the panoramic radiographies used to evaluate TME have certain restrictions and CTs have high level of radiation doses, they are not recommended for use. Hence, the use of CBCTs is highly suggested (21). A study confirmed that CBCT images are more reliable and accurate in condylar erosions compared to panoramic and tomographic radiographs (4). As temporomandibular dysfunctions constitute an important problem in certain orthodontic patients, TMJ evaluations before, during, and after orthodontic treatment are highly important (21). Furthermore, large FOV CBCT devices allow the display of neighboring structures reflected on TMJ (stylohyoid ligament, cervical spine, or other anatomic structures) that can cause pain.

Three-dimensional Display of Dentition

CBCT displays dental morphology, in other words, roots and crowns, missing, supernumerary or abnormal teeth, localization of teeth and roots, and eruption process in a mixed dentition phase as three-dimensional and without distortion (8). This provides information to the clinician about the dental development phases and proper treatment strategy (guidance of eruption, serial extraction, and various orthodontic mechanics). A panoramic view of dentition captured with CBCT is similar to the conventional panoramic view, but a healthier display of dentition is provided because the contralateral side and the vertebrae do not have a superimposition and projection artefact (12). In cross sections, the right and left tooth pairs, asymmetries, and position of teeth and roots against the buccal and lingual cortical bones. Occasionally, a very thin alveolar bone may be present in this area, and the condition that cannot be detected with

conventional orthodontic records may allow the orthodontist to ensure a better treatment plan (12).

Kamburoğlu et al. (40) evaluated the precision and repeatability of dental volumetric tomography in the measurement of the length of cadaver teeth. Eighteen healthy teeth of two cadaver mandibles were displayed in the study by using 6- and 9-inch scan areas with the help of dental volumetric tomography (NewTom 3G Plus). After the digital lengths of teeth were measured over sectional displays, their real lengths were measured with the help of a digital caliper. While the average difference between the length measurements with digital caliper and images taken with 6-inch scanning area was 0.17 mm, this difference was 0.16 mm in images taken with the 9-inch scanning area. These differences are statistically insignificant. Precise and repeatable results were obtained in tooth length measurements by using dental volumetric tomography.

Digital models can be obtained from CBCT data. Thus, the need for measurement is eliminated. Erupted and unerupted teeth and roots, alveolar bone, and supernumerary teeth can be displayed in these models (41, 42). Measurement accuracies of the models obtained from CBCT data and OrthoCAD digital models were compared in a study. It was reported that linear measurements in models obtained from CBCT were the same as that with OrthoCAD models (42).

Orthognathic Surgical Applications
It is possible to generate virtual anatomic models using CBCT volumes. These virtual models can then be used to simulate treatment options in a virtual environment. Therefore, they become an important tool in the surgical procedure. These databases can be used to simulate the response of tissues to growth, treatment, and functional conditions in a virtual environment through anatomic models created with the help of CBCT volumes; for example, facial soft tissues can be correlated with viscoelastic structures and connected with hard tissues lying at the bottom. Therefore, virtual manipulation of hard tissues allows observation of the change in the concerned soft tissues (28).

Evaluation of Asymmetries
It is very hard to evaluate bone asymmetries by using cephalometric or panoramic radiographies. Structure superimposition, standardization of the head position, and distortion can create substantial problems. However, bilateral structures (such as the corpus, ramus, and condyl) can be evaluated with CBCT images, and the mandibular asymmetry can be detected. Softwares allow differentiation between the maxilla or the mandible from other images and their evaluation separately. Moreover, it can be determined whether the unilateral crossbite is real or is a result of dislocation of the mandible while entering the centric occlusion. The clinician can display the maxilla and the mandible in various angles and evaluate them in terms of asymmetry with the CBCT image that is taken only once instead of taking numerous two-dimensional radiographs (21).

Evaluation of Cleft Lip and Palate and Alveolar Bone Grafts
CBCT allows displaying the morphology of the bone defect, closeness of the neighboring teeth to the defect, and supernu-

merary or malformed teeth around the cleft. The bone amount necessary for the treatment of the defect and the proper surgical treatment plan is determined. Success of the located bone graft, relations of neighboring teeth with this graft, and periodontal conditions of teeth are evaluated. Therefore, it is determined whether the neighboring teeth can be moved or whether it is possible to place an implant (12). A study evaluated the success of alveolar bone grafts by using CBCT and panoramic radiography and reported that it was possible to evaluate the vertical bone height of the panoramic radiography, but it did not give an idea about the bone amount in the buccopalatal direction (43). For this reason, it is recommended to take images using CBCT in cleft lip and palate patients.

Facial Analyses
Two-dimensional or three-dimensional facial images can be superimposed on CBCT images. Thus, the face can be displayed as frontal, lateral, or from any desired angle. By changing the translucency of the image, relations between soft and hard tissues can be evaluated. This is highly important in planning teeth movements, orthognathic surgery, or other applications that can change the facial view. However, it should be considered that the soft tissue view can change depending on the patient immobilization technique (supine position, sitting, or standing). Furthermore, the forehead or jaw retainer tools used in stabilization of the head can cause distortion in the soft tissues (12).

Cephalograms Obtained from CBCT
Lateral cephalometric radiographies can be generated from CBCT data and conventional measurements can be conducted and compared with two-dimensional norms. Conventional cephalometric radiographies are taken with a technique called perspective projection, and the magnification occurs depending on the distance between the object and film (12). The part close to the film is magnified less compared to the part far from the film, and a double edge view occurs on the mandible (8). There is no magnification in CBCT because the three-dimensional view is generated from raw data with a mathematical algorithm and this algorithm, even if the X-rays are not parallel, has the ability of eliminating the occurring magnification (8). Judging by the other advantages of this method; even if the patient's head is not positioned appropriately during scanning, it can be repositioned in a digital environment, and the image quality can be increased by excluding the structures that are not related to the scan area and are superimposed; separate images can be created for the right and the left side (8).

No difference was detected between the lateral cephalometric films generated from CBCT and conventional cephalometric films with linear and angular measurements (44, 45).

Anteroposterior cephalometric radiographies can be obtained from CBCT data. The advantages of this method are the ability of positioning the head in a digital environment and preventing superimposition of the vertebra and the occipital bone (3, 11).

Cephalometric landmarks can be created on three-dimensional data using recently developed software. Thus, it will be possible

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to use new anatomic landmarks that are not visible on two-dimensional cephalometric films and to measure new angles and distances. A three-dimensional norm can be created by morphometric characteristics and three-dimensional images taken from patients can be superimposed on this norm. Superimposition can be made on CBCT images taken from the same patient at a different time and changes occurring due to growth or the effect of the treatment can be determined (8, 12). This superimposition is made on the entire cranial bottom surface in patients who have completed their growth, and it is performed on the anterior surface of the cranial bottom in patients who have not yet completed their growth (46).

Three-dimensional measurements on CBCTs can be made in various imaging modes. These are MPR, VR, and SSD modes (47, 48). A measurement is made between points in MPR, and it is highly accurate when compared to direct measurements on skulls. In the VR and SSD modes, the surface anatomy is measured, and a 2.3% measurement error was detected when compared to direct physical measurements (48, 49). These findings indicate that landmark identifications should be made in MPR mode.

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CONCLUSION

CBCT accurately and comprehensively defines the proper diagnosis, treatment, and craniofacial anatomy for a good prognosis. CBCT, used in many branches of dentistry, has found itself a broad place in orthodontics in recent years. Orthodontics shifts from lines, lengths, and angles to spaces, surfaces, and volumes. Numerous developments are expected in this field in the future. However, as CBCT generates a high level of radiation despite being a highly beneficial tool, it should only be applied when conventional radiography is insufficient to provide the required information.

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