



Cone Beam Computed Tomography In Orthodontics – A Comprehensive Review

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Abstract

Cone Beam Computed Tomography (CBCT), a three-dimensional imaging which has fundamentally transformed orthodontic diagnosis, treatment planning, and biomechanics by overcoming the magnification errors, projection distortion, and structural superimposition inherent in conventional two-dimensional imaging. CBCT generates volumetric datasets comprising of isotropic voxels, providing sub-millimetre dimensional accuracy across axial, sagittal, coronal, and oblique planes. Clinically, CBCT offers unmatched diagnostic applications including the precise 3D localization of unerupted, impacted, and supernumerary teeth, early detection and volumetric quantification of orthodontically induced root resorption, and the objective assessment of transverse and skeletal asymmetries. Additional applications include evaluation of the temporomandibular joint, pre- and postoperative alveolar cleft defect analysis, and temporary anchorage device placement planning. Modern orthodontic workflows increasingly integrate CBCT data for voxel-based cranial base superimpositions, automated airway segmentation, virtual surgical planning, orthognathic surgical simulation, and hybrid digital model generation using optical surface scans. CBCT delivers considerably lower radiation exposure than conventional medical computed tomography, ionizing radiation doses vary from 9 to 300 μ Sv.

Consequently, clinical utilization must strictly adhere to radiation protection principles, by justifying its indications and enhancing the clinical outcomes.

Keywords: Cone Beam Computed Tomography, Orthodontics, Radiation protection, Root Resorption, Three-Dimensional Imaging, Virtual Surgical Planning

Introduction

The diagnostic phase represents one of the most critical components of comprehensive orthodontic treatment planning. Accurate assessment of the craniofacial skeletal morphology, dental relationships, soft tissue contours, and pathological conditions is fundamental to formulating an effective and individualized treatment protocol [1]. Historically, orthodontists relied upon conventional two-dimensional imaging modalities, including intraoral periapical radiographs, panoramic radiographs, and cephalometric projections [2]. However, traditional

imaging methods present inherent limitations regarding dimensional accuracy, soft tissue visualization, and complex 3D anatomical spatial relationships [3]. The introduction of Cone Beam Computed Tomography (CBCT) into dentistry in 1998 represented a paradigm shift [4]. CBCT provides volumetric 3D imaging with significantly reduced radiation exposure, minimal patient discomfort, and enhanced diagnostic accuracy compared to medical CT [5][6]. It offers advantages in complex scenarios involving impacted teeth, skeletal

discrepancies, cleft palate management, TMJ assessment, and orthognathic surgical planning [7]. The isotropic voxel architecture enables multiplanar images in any orientation [8]. Software applications permit 3D econstruction, virtual simulation, and volumetric quantification [9]. Despite these advantages, the principle of 'as low as reasonably achievable' (ALARA) mandates case-specific justification [10].

Historical Evolution of Imaging Technology in Orthodontics

Prior to radiographic technology, orthodontic diagnosis depended on subjective clinical observation [11][12]. The discovery of X-rays by Röntgen in 1895 brought 2D intraoral radiography [13][14]. Panoramic radiography in the mid-20th century allowed broad single-exposure visualization of both dentitions, though limited by 2D projection and distortion [15]. Cephalometric radiography, pioneered by Broadbent in 1931, established standardized quantitative assessments of sagittal and vertical relationships [16][17][18]. However, 2D cephalometry suffered from projection errors, superimposition of bilateral structures, and loss of transverse dimension data [19][20]. Medical fan-beam CT provided 3D imaging but caused high radiation, high cost, and severe metal restoration artifacts [21]. The development of CBCT in the late 1990s specifically overcome these limitations for dentomaxillofacial imaging [22][23].

Fundamental Principles of Cone Beam Computed Tomography

CBCT operates by rotating an X-ray source producing a cone-shaped beam and a 2D digital detector array synchronously around the patient through an angular arc of 180° to 360° [24][25]. This generates 150 to 600 basis images processed via filtered back-projection or iterative algorithms into volumetric datasets composed

of isotropic voxels [26][27]. Isotropic voxels ensure identical spatial resolution in axial, sagittal, coronal, and oblique planes [28][29]. The selection of Field of View (FOV)—ranging from limited (LFOV, 5-8 cm) to extended (EFOV, 15-20 cm)—directly determines radiation dose, spatial resolution, and area of anatomical visualization [30][31][32][33].

Technical Specifications and Parameters

Key exposure factors in CBCT include kilovoltage (70–120 kV) and tube current (mA), influencing contrast resolution, penetration, and radiation dose [34][35]. Detector technology has evolved from Charge-Coupled Devices (CCDs) to CMOS Flat-Panel Detectors (FPDs), offering pixel dimensions as fine as 0.15–0.20 mm with higher dynamic range and reduced noise [36][37]. Equipment configurations encompass seated, standing, and supine units designed to balance patient stability with physical mobility requirements [38][39].

Comprehensive Diagnostic Applications of CBCT in Orthodontics

Assessment of Unerupted, Impacted, and Supernumerary Teeth

Precise localization of unerupted, impacted, and supernumerary teeth is a premier application of CBCT [45]. Traditional 2D radiographs suffer from distortion and structural overlap, while CBCT delivers true 3D coordinates, spatial orientation, root morphology, and exact proximity to adjacent cortical plates and neighboring roots [45]. In maxillary canine impactions, CBCT evaluates the exact labiopalatal position, degree of inclination, and presence of root resorption on adjacent lateral incisors [45]. For supernumerary teeth (e.g., mesiodens), CBCT details inverted or impacted configurations, crown-root morphology, and safe surgical access vectors to avoid vital adjacent anatomical structures.

Table 1: Frequency of CBCT-Identified Diagnostic Changes in Impacted Teeth Cases

Diagnostic Criterion	Traditional Imaging (%)	CBCT Imaging (%)	Change Magnitude
Precise Tooth Position	42	94	52

Root Development Stage	56	98	42
Spatial Relationship to Adjacent Structures	38	89	51
Surgical Approach Determination	31	87	56

Assessment of Root Resorption

Orthodontically induced inflammatory root resorption (OIIRR) and pathological root resorption require early detection to alter treatment force protocols [46]. Conventional

periapical radiographs detect apical root loss only after significant mineral loss occurs. CBCT offers superior sensitivity, volumetric loss quantification, and precise localization across buccal, lingual, apical, and lateral root surfaces [46]. It enables clinicians to differentiate mild resorptive blunting from severe root loss, establishing objective criteria for pause or modification of active orthodontic tooth movement.

Skeletal Discrepancy and Transverse Asymmetry Assessment

Accurate 3D characterization of anteroposterior, vertical, and transverse skeletal relationships overcomes the major limitations of 2D lateral and posteroanterior cephalograms [47]. CBCT permits accurate quantification of mandibular asymmetry, maxillary transverse deficiency, midpalatal suture maturation, and differential ramus/condylar heights [47]. Reconstructed 3D cephalometrics eliminate projection errors and landmark displacement caused by head rotation, allowing true volumetric comparison between left and right sides.

Soft Tissue and Airway Evaluation

Volumetric soft tissue segmentation enables comprehensive assessment of facial soft tissue thickness, lip symmetry, and chin contour relative to underlying bony frameworks [48]. This is invaluable for orthognathic surgery planning and esthetic facial

analysis. In airway diagnosis, CBCT provides quantitative 3D volumetric rendering and minimum cross-sectional area (MCA) measurements of the nasopharynx, oropharynx, and hypopharynx [48]. This objective spatial analysis aids in evaluating patients with sleep-disordered breathing, obstructive sleep apnea (OSA), and vertical maxillary excess.

Temporomandibular Joint (TMJ) Assessment

CBCT provides sub-millimeter visualization of condylar osseous morphology, glenoid fossa dimensions, articular eminence inclination, and joint space intervals [49]. It excels at identifying condylar erosion, flattening, osteophytes, subchondral sclerosis, ankylosis, and developmental anomalies (e.g., condylar hyperplasia or hypoplasia) [49]. Dynamic evaluation of condylar translation and centric relation-centric occlusion (CR-CO) discrepancies helps clinicians customize biomechanics in patients presenting with temporomandibular disorders.

Cleft Palate Management and Alveolar Grafting

Cleft lip and palate represent complex 3D skeletal, dental, and soft tissue deformities. CBCT enables precise linear and volumetric measurement of cleft dimensions, evaluation of teeth adjacent to or within the cleft defect, and assessment of nasal septal deviation [50].

Postoperatively, CBCT provides direct volumetric measurement of secondary alveolar bone graft integration, height of regenerated alveolar bone, and eruption path monitoring for teeth erupting through the graft.

Table 2: Comparative Analysis of Diagnostic Accuracy in Cleft Palate Assessment

Sl.no	Assessment Parameter	Conventional Imaging	CBCT imaging
1	Cleft Width Measurement	Qualitative	Quantitative (mm)
2	Dental Relationships in Cleft Region	Limited visualization	Comprehensive 3D visualization
3	Bone Graft Integration	Indirect assessment	Direct volumetric measurement
4	Nasal Airway Assessment	Not possible	Complete characterization
5	Alveolar Bone Height	Estimated on radiograph	Precise 3D measurement

Temporary Anchorage Device (TAD) Placement Planning

Placement of mini-screws and TADs benefits directly from 3D anatomical mapping. CBCT allows measurement of cortical bone thickness, interdental distance (IDW), buccopalatal depth (BPD), and root proximity [40]. It facilitates identification of optimal placement safe zones in the interradicular space, palate, infrazygomatic crest, and mandibular buccal shelf, while preventing accidental root perforation or sinus penetration [40]. Furthermore, CBCT data can be coupled with rapid prototyping to fabricate 3D stereolithographic surgical guides for accurate TAD insertion.

Treatment Planning and Case Selection

Judicious prescription of CBCT requires justification based on clinical need where diagnostic data directly influences treatment decisions. AAOMR and ADA guidelines recommend CBCT for impacted teeth, severe 3D skeletal discrepancies, presurgical orthognathic planning, cleft palate assessment, TAD placement in complex anatomical sites, and TMJ pathology evaluation. Routine CBCT scanning for mild crowding, simple Class I malocclusions, or asymptomatic patients is not supported.

Advanced Clinical Applications

Virtual Treatment Simulation and Orthognathic Surgical Planning

Advanced software utilizes CBCT volumetric datasets for 3D virtual setups, predicting tooth movement trajectories, and simulating orthognathic surgical procedures [41]. Virtual Le Fort I and mandibular osteotomies allow virtual repositioning of skeletal segments, splint fabrication via CAD/CAM, and accurate prediction of hard-to-soft tissue change ratios [41].

Voxel-Based Superimposition and Growth Assessment

Sequential CBCT scans obtained at different treatment timepoints (T1, T2) can be superimposed using automated voxel-based alignment on stable anterior cranial base structures [42]. Achieving sub-millimeter precision (approx. 0.5 mm), voxel-based superimpositions track exact patterns of craniofacial growth, dentoalveolar decompensation, anchorage loss, and surgical relapse far more accurately than 2D cephalometric trace superimposition.

Digital Model Generation and Hybrid Workflows

CBCT datasets can be segmented to create 3D digital dental models containing complete root morphology and surrounding bone level boundaries [43]. Merging CBCT DICOM files with intraoral optical surface scans (.STL) generates high-fidelity hybrid models.

These hybrid setups are essential for clear aligner manufacturing, custom lingual bracket positioning, and root-aware virtual setups [43].

Quantitative Volumetric Airway Analysis

Automated segmentation tools compute total airway volume, regional airway breakdown (retropalatal, retroglossal), and narrowest constriction points [44]. This allows precise pre-and post-treatment evaluation following rapid maxillary expansion (RME), mandibular advancement splints, or maxillomandibular advancement (MMA) surgery.

Comparative Analysis: CBCT versus Conventional Imaging

CBCT delivers superior dimensional accuracy (within $\pm 1\text{--}2\%$ or sub-millimeter error) compared to panoramic ($\pm 12\text{--}15\%$) and cephalometric ($\pm 6\text{--}8\%$) projections. It eliminates superimposition distortion, magnification variations, and structural foreshortening. Although MRI remains superior for soft tissue disc visualization, CBCT provides an optimal balance of hard tissue clarity and integrated soft tissue profile rendering for orthognathic and orthodontic management.[45]

Table 3: Dimensional Accuracy Comparison Between Imaging Modalities

Measurement	Panoramic Accuracy	Cephalometric Accuracy	CBCT Accuracy
Anteroposterior Dimension	$\pm 15\%$	$\pm 8\%$	$\pm 2\%$
Vertical Dimension	$\pm 12\%$	$\pm 6\%$	$\pm 1.5\%$
Transverse Dimension	Not measurable	Not measurable	$\pm 1\%$
Asymmetry Quantification	Qualitative only	Qualitative only	Quantitative $\pm 2\text{mm}$

Radiation Dosimetry and Biological effects

Effective radiation doses for CBCT range from $9\text{ }\mu\text{Sv}$ (limited FOV, rapid scan) to $300\text{ }\mu\text{Sv}$ (extended FOV, high-resolution). For comparison, annual natural background radiation is approximately $2,000\text{--}3,000\text{ }\mu\text{Sv}$, while a panoramic radiograph is $\sim 2.7\text{--}5.3\text{ }\mu\text{Sv}$ and medical CT is $500\text{--}1,000\text{ }\mu\text{Sv}$. Radiation protection dictates adherence to ALARA/ALADA (As Low As Diagnostically Acceptable) principles, utilizing collimation and low-dose pediatric protocols.[46][47]

Table 4: Effective Dose Comparison Among Radiographic Modalities

Imaging Modality	Effective Dose (μSv)
Single Intraoral Periapical Radiograph	0.3
Panoramic Radiograph	2.7-5.3
Lateral Cephalometric Radiograph	2.7-4.8
Medical Fan-Beam CT (Head)	500-1000
CBCT - Limited Field of View	9-50

CBCT - Extended Field of View (Standard Protocol)	50-100
CBCT - Extended Field of View (High-Resolution Protocol)	100-300

Limitations and Artifacts

Inherent limitations of CBCT include reduced soft tissue contrast resolution, inability to evaluate early pulp/soft tissue infection, and vulnerability to image degradation from artifacts. Artifacts include patient motion blur, beam hardening, streaking caused by metallic dental restorations or fixed orthodontic brackets, and cupping artifacts.

Future Perspectives and Technological Advancements

Emerging developments in CBCT focus on Artificial Intelligence (AI) and deep learning convolutional neural networks (CNNs) for automated landmark identification, automatic anatomical segmentation, and noise reduction [48]. Deep learning algorithms enable high-quality reconstruction from Ultra-Low-Dose (ULD) scans. Additionally, integration with

dynamic real-time surgical navigation and multimodal image fusion (CBCT + MRI + Optical Scans) will expand future clinical utility.

Conclusion

CBCT has transformed orthodontic diagnosis and treatment mechanics by providing true 3D spatial clarity. Its application in impactions, skeletal discrepancies, root resorption, TMJ assessment, TAD planning, and virtual surgery elevates diagnostic accuracy and treatment outcomes. Adherence to evidence-based guidelines and ALARA principles ensures maximum diagnostic efficacy with optimal patient safety.

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