

Cone Beam Computed Tomography in Orthodontics: Evolution, Clinical Applications, And Diagnostic Accuracy — A Narrative Review

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Abstract—Orthodontic diagnosis and treatment planning have traditionally relied on two-dimensional (2D) radiographic techniques such as cephalometric radiography and panoramic imaging. These methods are limited by magnification, geometric distortion, superimposition of structures, and projective displacement. Cone beam computed tomography (CBCT) has emerged as a low-dose, chairside three-dimensional (3D) imaging modality that overcomes many of these limitations and has been rapidly adopted across orthodontic and maxillofacial practice.

Index Terms—Cone beam computed tomography; orthodontics; three-dimensional imaging; radiation dose; cephalometry; diagnostic accuracy

I. INTRODUCTION

In 1895, Wilhelm Conrad Röntgen discovered X-rays and provided the first description of a previously unknown form of electromagnetic radiation, an event that would prove decisive for the diagnosis of disease.¹ Over the following century, improvements in imaging technology transformed dental radiology, giving it a central role in diagnosis, treatment planning, and prognosis. Orthodontic imaging has always sought comprehensive visualisation of the craniofacial complex, and to this end two-dimensional (2D) techniques — conventional radiographs, cephalometric tracings, photographs, and video imaging — have been the mainstay of practice. The constraints of these 2D modalities are well recognised

and include magnification, geometric distortion, superimposition of structures, projective displacement (elongation or foreshortening), rotational error, and linear projective transformation.^{1,2}

Three-dimensional (3D) imaging permits assessment of the true anatomical form of the structure being examined. Historically, 3D information in orthodontics was limited to plaster study models and, more recently, digital models combined with clinical examination.^{3,4,5} Over the past two decades, cone beam computed tomography (CBCT) has become an increasingly important source of 3D volumetric data in orthodontics. Despite its growing use, data obtained from CBCT and other imaging modalities have not always been fully integrated into an accurate 3D representation of a patient's anatomy — a "virtual patient" — and the specific indications, protocols, and evidence base for CBCT use continue to be refined.

CBCT has attracted an unprecedented degree of attention across dental disciplines because it has shifted maxillofacial diagnosis from 2D to 3D imaging and extended the use of imaging from diagnosis alone to image-guided surgical and operative procedures.⁶ The most common indications for cone-beam imaging in dentistry are assessment of the jaws for implant placement, evaluation of teeth and facial structures for orthodontic treatment planning, assessment of the temporomandibular joints (TMJs), evaluation of impacted teeth and their proximity to vital structures, assessment of root fracture or periapical disease, and detection of osseous infection, cysts, or tumours. All

of these applications benefit from the ability to view thin slices through a region of interest without superimposition of complex local anatomy.⁶

Relative to conventional CT, CBCT offers voxel isotropy, high-speed scanning, submillimetre resolution, a variable field of view (FOV), multiplanar reformatting, and display modes unique to maxillofacial imaging, and these attributes underlie its growing popularity for diagnosis and treatment planning. Realising this potential, however, requires that the clinician understand normal anatomy, the radiological appearance of disease and artefact, and the software tools needed to generate accurate curved and cross-arch measurements. Opinions on the appropriate breadth of CBCT use in orthodontics continue to vary, from routine use in all patients to selective use restricted to specific indications such as cleft palate, evaluation of unerupted-tooth position, identification of resorption caused by unerupted teeth, and orthognathic surgical planning, where conventional radiography cannot provide sufficient diagnostic information.⁷ Clinicians without adequate training in CBCT interpretation may have a high error rate, resulting in missed or false-positive diagnoses.⁷ This review aims to familiarise the reader with the principles of multiplanar imaging made possible by CBCT and to summarise its emerging and established role in orthodontic diagnosis, treatment planning, and outcome evaluation.

II. HISTORICAL EVOLUTION OF RADIOGRAPHIC IMAGING IN ORTHODONTICS

The cephalometer, invented by B. Holly Broadbent in 1931, marked the beginning of radiographic imaging in orthodontics.⁸ It was initially used to study normal craniofacial growth, and several major longitudinal growth studies were conducted between 1932 and 1970,⁹ forming the basis of our current understanding of facial growth. Cephalometrics allowed changes in facial growth to be studied over time: by tracing serial radiographs and superimposing them on stable anatomical structures of the cranial base, changes in facial bones and teeth — and the effects of orthodontic treatment on the growing face — could be reliably assessed. However, the projection of 3D facial and skull anatomy onto a 2D film inevitably resulted in loss or distortion of parasagittal information.

Cephalometric analysis is now regarded as an indispensable component of orthodontic diagnosis, although its integration into clinical practice occurred gradually. The first cephalometric analysis was not published until 1948, by Downs,¹⁰ initially as a research tool; it took a further 15 years before clinical adoption became widespread. Numerous subsequent methods of cephalometric analysis have been described, but none has gained universal acceptance.¹⁰ Across these analyses, the recurring areas of clinical interest have been the position of the maxilla and mandible relative to the cranial base, the position of the upper incisors relative to the maxilla, the position of the lower incisors within the mandible, and vertical facial balance.

By 1950, nearly all orthodontists possessed a cephalometer, and by 1960 the American Board of Orthodontics required before-and-after cephalograms for board-certified cases. In the early 1980s, 2D digital imaging was introduced, and in 1998 a composite system combining digital lateral cephalograms with digital facial photographs was described for patient communication and treatment planning.¹¹ Despite these advances, 2D digital imaging did not fundamentally add new morphological information, and market penetration remained limited.

The term "tomography" derives from the Greek *tomos* ("slice") and *graphia* ("picture, description") and was adopted in 1962 by the International Commission on Radiological Units and Measurements to describe body-section radiography generally. Computed tomography (CT) was independently developed by Sir Godfrey Hounsfield and Dr Allan Cormack, work for which they were jointly awarded the Nobel Prize in 1979.¹² The first clinical CT scanner, the "EMI Scanner," produced only 80 × 80-pixel tomographic images of the brain, requiring approximately seven minutes of computation per image; the first clinical scan was performed in 1972 at Atkinson Morley Hospital, London.¹³

CBCT itself was first developed for clinical use in 1982 at the Mayo Clinic Biodynamic Research Laboratory, initially for angiography applications prioritising temporal and spatial resolution over soft-tissue contrast. Use of cone-beam geometry for radiotherapy guidance began in 1992, and by 1999 a CBCT system had been integrated into a linear-accelerator gantry. The first commercial dentomaxillofacial CBCT system, the NewTom QR

DVT 9000 (Quantitative Radiology, Verona, Italy), was released in 2001 and received FDA approval that year, marking the formal beginning of 3D dental imaging.¹⁴ Its moderate radiation dose and relatively compact footprint generated enthusiasm for applications ranging from surgical planning to intraoperative guidance in head and neck, spinal, thoracic, abdominal, and orthopaedic procedures.¹⁴ The competitive orthodontic marketplace subsequently contributed to CBCT's rapid diffusion, as practices sought to differentiate themselves through access to advanced imaging technology.

III. PHYSICAL PRINCIPLES AND IMAGE ACQUISITION

CBCT produces 2D and 3D images by rotating an x-ray tube and a 2D digital detector through at least 180° (typically 360°) around the patient. The size of the imaged volume — the field of view (FOV) — is determined by detector dimensions, beam geometry, and system settings. Unlike hospital fan-beam CT, which uses a thin, fan-shaped beam to acquire sequential axial slices that must subsequently be reformatted into a volume, CBCT captures the entire region of interest in a single rotation using a rectangular or round 2D detector. This geometry offers more efficient use of the radiation beam, faster volumetric acquisition, lower equipment cost, and — critically — isotropic voxels, which permit equally precise measurement in all three spatial dimensions.¹⁵ Image formation occurs in two stages. During acquisition, a sequence of 2D projection ("basis") images is captured as the source–detector arm rotates; the number of projections depends on frame rate and exposure cycle, with higher frame rates providing more data at the cost of a reduced signal-to-noise ratio per slice. During reconstruction, the projection data are corrected for geometric and visual distortion and processed through a reconstruction algorithm to generate a single volumetric dataset, typically within five minutes to preserve clinical workflow.¹⁵

Three broad categories of dentomaxillofacial CBCT system exist: (i) large-FOV systems capable of imaging a substantial portion of the maxillofacial and cranial complex in a single exposure; (ii) dedicated small-FOV systems; and (iii) hybrid panoramic/CBCT systems, some of which also provide a 2D digital cephalogram option. Large-FOV systems can generate

simulated 2D cephalograms directly from CBCT data, in addition to an expanding range of 3D analyses, physical biomodels, and image-guidance applications for surgery and implant placement.

IV. RADIATION DOSE CONSIDERATIONS

Comparing radiation doses across imaging modalities is not straightforward, because surface exposure alone does not account for beam size or the differing radiosensitivity of exposed tissues. To enable meaningful comparison, exposures are converted to effective dose, expressed in Sieverts (Sv) or its subunits (mSv, μ Sv), which weight the absorbed dose to each organ by its radiosensitivity and sum these weighted values across the tissues defined by the International Commission on Radiological Protection (ICRP).^{16,17} For head imaging, the thyroid and salivary glands make a particularly important contribution to effective dose because of their proximity to the beam.

Published effective doses for digital panoramic radiography range from 2.4–6.2 μ Sv (excluding salivary glands) to 5.5–22.0 μ Sv (including salivary glands); digital cephalometric radiography ranges from 1.6–1.7 μ Sv to 2.2–3.4 μ Sv under the same conventions.^{18,19} By comparison, dosimetry studies of large-FOV CBCT systems report substantially higher — though still comparatively modest — effective doses: 36.3–77.9 μ Sv for the NewTom 9000, 44.5–58.9 μ Sv for the NewTom 3G, 68.7–104.5 μ Sv for the 9-inch i-CAT, 134.8–193.4 μ Sv for the 12-inch i-CAT, and 846.9–1025.4 μ Sv for the CB MercuRay, depending on FOV and whether salivary-gland dose is included.^{20,21} Several authors have confirmed that CBCT delivers a radiation dose roughly 40% lower than conventional multidetector CT, while remaining approximately three- to seven-fold higher than panoramic radiography — reinforcing that CBCT, rather than medical CT, should be the modality of choice whenever 3D information is clinically required.

V. GUIDELINES FOR THE USE OF CBCT IN ORTHODONTICS

The decision to use CBCT requires careful weighing of the potential diagnostic and therapeutic benefit against the radiation risk, particularly in children and adolescents, who are more radiosensitive than adults.

The American Academy of Oral and Maxillofacial Radiology, incorporating advisory input reflecting the ALARA ("as low as reasonably achievable") principle, has proposed four overarching principles for CBCT use in orthodontics:²²

1. Image appropriately according to the clinical condition;
2. Assess the radiation dose risk;
3. Minimise patient radiation exposure; and
4. Maintain professional competency in performing and interpreting CBCT studies.

In practical terms, CBCT should be reserved for situations in which lower-dose conventional radiography or non-ionising modalities cannot answer the clinical question; it should not be used solely to generate a virtual cephalogram or panoramic view if this would increase overall exposure relative to conventional imaging; and, when acquired, the FOV, milliamperage, kilovoltage, number of basis images, and resolution should be limited to the minimum necessary to visualise the region of interest.²² To assist standardised risk communication, Reference Radiation Levels have been proposed, expressing effective dose relative to comparable imaging modalities, background-equivalent radiation time, or radiation detriment (stochastic cancer risk per unit exposure).

VI. CLINICAL APPLICATIONS OF CBCT IN ORTHODONTICS

6.1 Three-Dimensional Treatment Planning and the "Virtual Patient"

CBCT enables patient-specific anatomic reconstruction (PSAR), a 3D representation of the patient that can be viewed from any angle, sliced, or rendered transparent to reveal underlying dental and osseous structures. This model can be manipulated for orthodontic or orthognathic surgical treatment planning, representing a shift toward more precise, individualised diagnosis. A related development is the use of the "axes of inertia," a 3D geometrical construct that characterises the spatial distribution of teeth and dental arches from CBCT data; in a series of 205 subjects, parallelism of the arch axes of inertia and coincidence of their centres of gravity on a common vertical axis indicated dentoalveolar symmetry, allowing patients to be classified into defined morphological categories to guide diagnosis.^{23,24}

6.2 Three-Dimensional Cephalometric Analysis

Conventional 2D cephalometry provides only a single projection at a time and cannot fully capture 3D craniofacial morphology; medical CT can, but its cost, limited availability, and higher radiation dose make it impractical for routine orthodontic use. CBCT overcomes these barriers, although the accuracy of 3D cephalometric analysis remains influenced by scan-volume size and the positional dependency of image values within the FOV.²⁵ Many clinicians currently reformat CBCT volumes into conventional 2D lateral and frontal cephalograms and panoramic views to permit comparison with historical 2D norms.

CBCT-derived cephalograms offer specific advantages over film-based cephalograms. Conventional lateral cephalograms use perspective projection, which inherently magnifies structures according to their distance from the film and can produce a double image of the mandibular border, making it difficult to distinguish true asymmetry from projectional artefact. CBCT reconstruction corrects this magnification, producing an orthogonal image that can be calibrated to a true 1:1 scale.^{26,27} Because the head position can be corrected digitally in three planes, CBCT also allows independent analysis of each side of the face and improves detection of true asymmetry. Similarly, CBCT-derived frontal cephalograms eliminate superimposition of the cervical spine and occipital bone, which otherwise limits the diagnostic value of conventional posteroanterior cephalograms for facial asymmetry. Landmark identification error on CBCT-derived cephalograms is comparable to that on conventional digital cephalograms, and specific landmarks, such as Basion, are more reliably located on CBCT-derived images.²⁸ The improved visualisation of individual root position, alveolar bone support, and root proximity afforded by CBCT is particularly valuable in mixed dentition, supernumerary teeth, and impacted-tooth assessment.

6.3 Three-Dimensional Review of the Dentition and Alveolar Bone

Volumetric review of the dentition allows identification of missing, impacted, or supernumerary teeth; staging of dental development; measurement of tooth size; and identification of root anomalies that could hinder tooth movement.²⁹ In the mixed dentition, CBCT clearly demonstrates all erupted,

erupting, and developing teeth and their root formation in three planes of space.³⁰ Buccal bone height and thickness can be quantitatively assessed with high precision,³¹ although measurement accuracy is influenced by bone thickness and imaging resolution.³² Early identification of thin alveolar bone allows orthodontists to modify treatment mechanics or involve other specialists, and volumetric analysis assists surgeons in assessing cortical bone thickness at planned osteotomy sites.

CBCT also permits classification of root resorption by type and location, including in multirooted teeth, and detection of radiopaque lesions such as enostosis, condensing osteitis, dense bone islands, and focal osteopetrosis near root apices — lesions that are highly prevalent in the mandible (88–100% of cases) and that may impede tooth movement or predispose to root resorption if teeth are moved against them.^{33,34,35,36,37} Cross-sectional visualisation of the incisor apices in relation to the nasal floor can also inform biomechanical decisions in deep-bite correction, for example by favouring posterior extrusion over anterior intrusion when vertical bone availability is limited.

CBCT-based assessment of alveolar bone height has been proposed as superior to conventional periodontal probing, since surface irregularities can extend between roots in ways not detectable by probing alone,³⁸ and is of particular value for evaluating candidate sites for temporary anchorage devices, including interproximal root space, palatal cortical bone thickness, and local bone density.

6.4 Alveolar Bone Dehiscence and Fenestration

Detection of alveolar bone dehiscence and fenestration is a widely studied CBCT application, given its relevance to periodontal risk during tooth movement. Comparative studies using surgical exposure as the reference standard have generally found that CBCT is sensitive for detecting these defects but tends to overestimate their true prevalence and dimensions. In a cohort of 14 patients undergoing accelerated osteogenic orthodontic surgery, CBCT was found to be moderately useful for detecting naturally occurring dehiscences and fenestrations but tended to overestimate the actual measurements relative to direct intraoperative assessment.³⁹ In a subsequent surgical-exposure validation study of 16 patients with Class I malocclusion and lower-anterior crowding,

CBCT detected approximately 2.5-fold more dehiscences and nearly three-fold more fenestrations than direct clinical examination; sensitivity for both defects approached 100%, but specificity ranged from 45.5–86.7% (dehiscence) and 50–86.7% (fenestration), and CBCT again overestimated linear measurements relative to the surgical gold standard.⁴⁰ Taken together, these findings suggest that while CBCT is a highly sensitive screening tool for alveolar bone defects, clinicians should interpret absolute measurements cautiously and be aware of a systematic tendency toward overestimation.

6.5 Root Resorption

External root resorption (ERR), particularly involving the maxillary incisors, is difficult to detect reliably on periapical or panoramic radiographs because of superimposition and 2D projection error. A systematic review comparing CBCT with periapical radiography for detecting ERR, based on 15 studies drawn from 720 screened records, found substantially higher sensitivity for CBCT (0.89) than for periapical radiography (0.68), supporting CBCT as the more reliable modality for suspected ERR.⁴¹ These findings are consistent with the broader literature suggesting that CBCT provides more accurate localisation and quantification of resorptive defects than conventional 2D imaging, informing both diagnosis and biomechanical treatment decisions.

6.6 Temporomandibular Joint Imaging

CBCT is particularly well suited to evaluation of the temporomandibular joints (TMJs), permitting both volumetric and multiplanar sectional review in planes parallel or perpendicular to the long axis of the condyle.^{42,43,44} Coronal views, historically difficult to obtain with conventional techniques, are readily generated with high resolution and without superimposition. Comparative studies have reported significantly higher diagnostic specificity for CBCT (0.95 ± 0.05) than for conventional panoramic radiography (0.64 ± 0.11), TMJ-specific panoramic radiography (0.55 ± 0.11), or linear tomography (0.58 ± 0.15) in evaluating osseous TMJ morphology.⁴⁵ While magnetic resonance imaging remains the reference standard for evaluating the articular disc and soft-tissue components, CBCT is considered excellent for assessing the bony components of the joint.

6.7 Airway and Sinus Assessment

Obstructive sleep apnoea (OSA), characterised by pauses in airflow of more than 10 seconds during sleep despite ongoing respiratory effort, is now as prevalent in the general population as asthma or diabetes, likely reflecting a combination of improved detection and the obesity epidemic.^{46,47,48} Because mouth breathing and airway obstruction are implicated in the aetiology of malocclusion, and conventional orthodontic records do not adequately characterise the airway, CBCT has become an important tool for 3D airway and sinus assessment.^{49,50,51} In a large clinical dataset, CBCT identified clinically significant airway findings in approximately one-quarter of patients imaged for orthodontic purposes. Volumetric CBCT analysis allows measurement of mandibular and maxillary deficiency, posterior airway space, tongue and soft-palate size, and hyoid position, and specialised software-based analysis has shown that patients with sleep apnoea have a smaller antero-posterior dimension and minimum cross-sectional area in the retropalatal airway than unaffected controls.⁵² Risk factors identified for OSA on CBCT-based airway analysis include age over 57 years, male sex, a high-risk Berlin Questionnaire score, and reduced upper-airway lateral dimension.⁵³

A repeated-measures study using standardised acquisition protocols in 27 patients scanned at two time points 4–6 months apart found that airway volumes measured from CBCT (nasopharynx, oropharynx, hypopharynx) showed high but not perfect reproducibility, with average inter-scan differences of several hundred to over 2000 mm³ depending on airway segment — underscoring the importance of standardised protocols and cautious interpretation when using CBCT volumetric data to draw clinical conclusions about airway change.¹⁵

6.8 Three-Dimensional Superimposition and Treatment Outcome Assessment

Three-dimensional superimposition allows two CBCT volumes acquired at different time points to be overlaid using either operator-defined landmarks or automated registration of stable cranial structures such as the anterior cranial fossa, enabling objective, distortion-free assessment of treatment effect, growth, and long-term stability.⁵⁴ Voxel-based registration, the most widely described and fully automated approach, is well suited to routine clinical use,

although quantitative evaluation of registration accuracy remains an area of ongoing methodological development.⁵⁵

6.9 Orthognathic Surgical Simulation and Image Fusion

Accurate simulation of surgical outcome is central to orthognathic treatment planning. Computer-assisted prediction serves a threefold purpose: guiding treatment toward a desired result, previewing the likely outcome for the patient, and functioning as a communication tool between orthodontist, surgeon, and patient.^{56,57} Early 2D computer-assisted cephalometric systems, first described in the late 1970s, permitted rapid measurement and combination of photographs, tracings, and radiographs but remained limited by their two-dimensional treatment of an inherently three-dimensional problem.^{58,59}

Modern workflows instead construct a patient-specific anatomic reconstruction (PSAR) by fusing CBCT/CT data with 3D facial-surface imaging, producing an integrated anatomical and biomechanical record rather than a set of separate images.⁶⁰ Fused surface imaging offers several practical advantages, including correction of CBCT surface artefact from patient movement, compensation for soft-tissue compression from head-stabilising devices, and restoration of anatomical detail (e.g., nose, chin) that may be incompletely captured by upright CBCT units.⁶¹ Registration is typically achieved by segmenting the outer surface of the CBCT dataset and aligning it to the independently captured facial-surface geometry, most often using anatomically stable regions such as the cheek and glabella; because reproducibility of manual facial landmarking can range from under 0.5 mm to 2 mm depending on the landmark, there has been ongoing methodological work toward standardised, clinically relevant landmark definitions and a shift from point-based to shape-based analysis.^{62,63,64,65,66}

6.10 Assessment of Dental Impactions

Diagnosis of impacted teeth using 2D radiography traditionally relies on the buccal object rule and paired images at right angles, an approach complicated when impacted teeth occupy atypical positions relative to the dentition or important anatomical landmarks. CBCT overcomes these limitations, enabling precise localisation of impacted teeth and their relationship to

adjacent structures, together with reformatted 2D and 3D reconstructions free of superimposition, distortion, or magnification.⁶⁷ Segmentation for 3D reconstruction typically involves Hounsfield-based thresholding (e.g., 300–1800 HU for mandibular bone), manual removal of metal-related artefact, and region-growing from an operator-selected seed point to isolate the anatomical structure of interest before final reconstruction.⁶⁷

Comparative studies have shown that CBCT is more sensitive than conventional radiography for localising impacted canines and identifying resorption of adjacent teeth, largely because 2D imaging is prone to distortion and blurring errors that CBCT avoids.^{68,69} These findings extend to implant, TMJ, and endodontic applications more broadly, where CBCT informs pre- and post-treatment evaluation of craniofacial structures.^{68,70}

VII. DIAGNOSTIC ACCURACY: EVIDENCE FROM COMPARATIVE STUDIES

A substantial body of comparative literature supports the superior accuracy of CBCT relative to 2D radiography across multiple orthodontic and maxillofacial applications. CBCT delivers approximately 40% less radiation than conventional multidetector CT while achieving voxel resolution as fine as 0.1 mm, compared with a practical resolution limit of around 0.5 mm for conventional CT.^{71,72,73,74} CBCT is recognised as a valuable diagnostic tool across oral and maxillofacial surgery, implantology, endodontics, and orthodontics, supporting assessment of implant recipient sites and bone defects, bone-graft planning, impacted-tooth localisation, orthodontic and endodontic treatment planning, TMJ disorders, sinus augmentation, and orthognathic surgery.^{68,75,70,76}

In implantology, CBCT provides accurate cross-sectional assessment of bone height and width, visualisation of the maxillary sinuses, lingual and mental foramina, and inferior alveolar canal, and simulated implant placement, reducing the risk of nerve injury (neuropraxia, axonotmesis, or neurotmesis) associated with panoramic-radiograph-guided planning.^{70,77,78} Conventional panoramic radiography has been shown to introduce clinically significant image enlargement and distortion relative

to CBCT, further supporting CBCT-guided pre-operative planning.^{71,74,79,80}

In endodontics, CBCT eliminates superimposition of periapical anatomy on adjacent roots and the zygomatic or alveolar bone, permits identification of accessory or previously undetected canals not visible on periapical radiographs, and detects a greater proportion of periapical lesions than conventional radiography — one in vivo study reported 25.9% more periapical lesions identified on CBCT than on periapical films during pre-surgical evaluation.^{81,76,73} CBCT has also demonstrated superior detection of anatomical variation relevant to surgical safety, including the position and course of the mandibular canal and mylohyoid nerve groove, relative to panoramic radiography.^{77,82}

Cephalometric point identification is also more accurate with CBCT-derived measurements than with conventional lateral cephalograms, and CBCT-based 3D surface modelling of facial anthropometry has shown greater accuracy, reproducibility, and efficiency than direct manual anthropometry in cadaveric studies.⁸³

Across these domains, the recurring pattern in the literature is that CBCT increases diagnostic sensitivity and measurement accuracy relative to 2D imaging, but that this gain in sensitivity is sometimes accompanied by a tendency to overestimate the true extent of small osseous defects (as seen with alveolar dehiscence and fenestration), underscoring the need for cautious, evidence-based interpretation rather than uncritical reliance on volumetric measurements.

VIII. LIMITATIONS AND CHALLENGES

Despite its advantages, CBCT has recognised limitations, including radiation exposure (still several-fold greater than panoramic radiography), a comparatively limited FOV relative to medical CT for some units, lower inherent soft-tissue contrast, and susceptibility to beam-hardening and scatter artefact from dental restorations, orthodontic appliances, and implants.⁸⁴ Ionising radiation remains the principal limiting factor governing CBCT use, and the ALARA principle should guide patient selection, FOV limitation, and exposure parameters at every stage of treatment.⁸⁴ Interpretation of CBCT data also requires specific training: clinicians unfamiliar with normal 3D anatomy and CBCT-specific artefact are at elevated

risk of diagnostic error, whether through missed pathology outside the primary region of interest or false-positive findings.⁷ As illustrated by the dehiscence/fenestration literature above, volumetric measurements can systematically overestimate small bony defects relative to direct surgical inspection, which should temper clinical interpretation of borderline findings.

IX. FUTURE DIRECTIONS

As digital workflows become increasingly integrated into orthodontic practice, several trends are likely to shape the future role of CBCT. These include continued refinement of low-dose acquisition protocols and ultra-low-dose paediatric imaging; wider adoption of automated, voxel-based 3D superimposition for outcome and stability assessment;⁵⁵ increasing use of image fusion between CBCT, 3D facial-surface scanning, and intraoral scanning to build increasingly accurate virtual patients for orthodontic and orthognathic surgical simulation; and growing application of automated landmark detection and artificial-intelligence-assisted image analysis to reduce operator-dependent variability in 3D cephalometric landmarking. Continued outcome-based research is required to refine evidence-based indications for CBCT, particularly for applications — such as routine screening for alveolar bone defects — where sensitivity gains must be weighed against a tendency toward overestimation and against cumulative radiation exposure across a course of orthodontic treatment.

X. CONCLUSION

CBCT has transformed orthodontic diagnosis and treatment planning by making distortion-free, volumetric visualisation of the craniofacial complex available at a fraction of the radiation dose and cost of medical CT. Its established and emerging applications span 3D cephalometric analysis, localisation of impacted teeth, alveolar bone and root-resorption assessment, TMJ and airway evaluation, and orthognathic surgical simulation, with comparative studies consistently favouring CBCT over 2D radiography for diagnostic accuracy. Realising these benefits responsibly requires strict adherence to evidence-based selection criteria and the ALARA

principle, adequate clinician training in 3D image interpretation, and cautious, calibrated interpretation of quantitative CBCT findings, particularly where systematic overestimation of small osseous defects has been demonstrated. As acquisition protocols, superimposition methods, and automated analysis tools continue to mature, CBCT is likely to become an increasingly standard, rather than adjunctive, component of orthodontic diagnostic practice.

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