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Cone Beam Computed Tomographic imaging in orthodontics

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ABSTRACT

Over the last 15 years, cone beam computed tomographic (CBCT) imaging has emerged as an important supplemental radiographic technique for orthodontic diagnosis and treatment planning, especially in situations which require an understanding of the complex anatomic relationships and surrounding structures of the maxillofacial skeleton. CBCT imaging provides unique features and advantages to enhance orthodontic practice over conventional extraoral radiographic imaging. While it is the responsibility of each practitioner to make a decision, in tandem with the patient/family, consensus-derived, evidence-based clinical guidelines are available to assist the clinician in the decision-making process. Specific recommendations provide selection guidance based on variables such as phase of treatment, clinically-assessed treatment difficulty, the presence of dental and/or skeletal modifying conditions, and pathology. CBCT imaging in orthodontics should always be considered wisely as children have conservatively, on average, a three to five times greater radiation risk compared with adults for the same exposure.The purpose of this paper is to provide an understanding of the operation of CBCT equipment as it relates to image quality and dose, highlight the benefits of the technique in orthodontic practice, and provide guidance on appropriate clinical use with respect to radiation dose and relative risk, particularly for the paediatric patient.

Keywords: Alveolar bone morphology, Cone beam computed tomography, Localized intrabony defects, Periodontal diagnosis, Root fractures.

Abbreviations and acronyms: ABH = alveolar bone height; CAB = crestal alveolar bone; CBCT = cone beam computed tomography; CEJ = cemento-enamel junction; CT = computed tomography; MPR = multi-planar reformation; DVR = direct volume rendering; ECR = external cervical resorption; ERR = external root resorption; FOV = field of view; GTR = guided tissue regeneration; HDM = high density materials; HU = Hounsfield units; IAC = inferior alveolar canal; IRR = internal root resorption; IVR = indirect volume rendering; LPC = lateral periodontal cyst; MIP = maximum intensity projection; MSDO = maxillary sinusitis of dental origin; PDL = periodontal ligament; PR = panoramic radiography; RBH = radiographic bone height; ROI = region of interest; SNR = signal to noise ratio; SS = shaded surface; ST-CBCT = soft tissue cone beam computed tomography; VBR = vertical bitewing radiography; VR = volumetric rendering.

INTRODUCTION

The purpose of radiographic imaging in orthodontics is to supplement clinical information supporting the clinical diagnosis of skeletal and dental conditions, soft tissues, and dento-maxillofacial inter-relationships. Orthodontic diagnosis and treatment plans, the evaluation of growth and development, and the assessment of treatment progress outcomes have traditionally been achieved by the integration of clinical and photographic data with findings and analysis of two-dimensional (2-D) radiography such as panoramic and lateral cephalometric imaging. For decades, the only true three-dimensional (3-D) documentation had been plaster study casts of the maxillary and mandibular dental arches.

The inherent limitations of 2-D radiography for maxillofacial assessment in orthodontics have been recognised for decades.[1,2] These include magnification, disproportional distortion, projective superimposition of anatomical details, errors and artifacts due to x-ray projection and patient positioning, and cephalometric measurement errors due to inherent difficulties in landmark identification. While used as the principal imaging modality in cephalometry, lateral cephalometric radiography demonstrates only a composite of antero-posterior and vertical relationships

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and little information on unilateral or transverse aspects of malocclusions or craniofacial anomalies. For an increasing number of orthodontic patients, an understanding of the complex anatomic relationships and surrounding structures of the maxillofacial skeleton is necessary for orthodontic planning to select the most appropriate therapy from the wider array of available treatment options.

ESSENTIALS OF CBCT IMAGING

Dental and maxillofacial cone beam computed tomography (CBCT) is a rapid acquisition technology that marks a shift in extraoral radiography from representative 2D images to a 3D anatomically accurate, volumetric dataset, expanding the role of imaging in orthodontic diagnosis. Recent reports document at least 20 vendors offering over 50 devices manufactured in many different countries.[3] To prescribe, perform or interpret CBCT images for orthodontics, clinicians should have a clinically-relevant understanding of the technical factors that influence image quality and radiation dose.

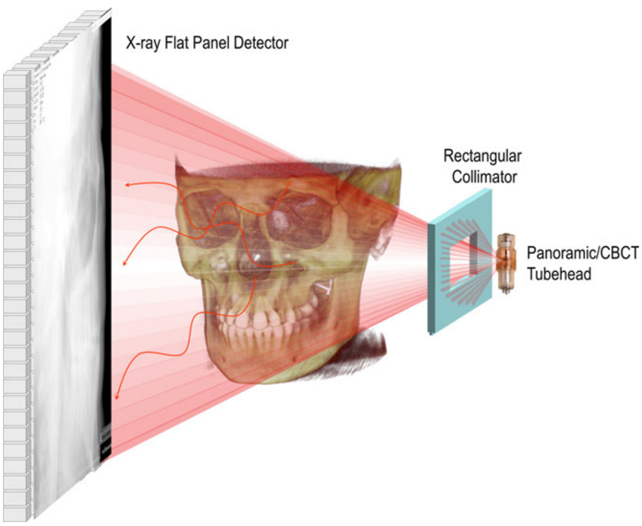

Fig. 1 Geometric configuration of X-ray beam projection and sensor for CBCT imaging. The amount of scatter generated (sinusoidal lines) and recorded by cone beam image acquisition is substantially higher, reducing image contrast and increasing image noise.

Acquisition

The current authors have described image acquisition in detail.[4–8] The unit comprises a rotating platform or imaging gantry capable of a single partial or full rotational scan. An x-ray source and a reciprocating digital area sensor synchronously revolve around a fixed axis of rotation centered within the patient's head. A divergent pyramidal- or cone-shaped beam of ionising radiation is directed towards the middle of the region of interest (ROI) onto an area x-ray sensor on the opposite side, with the imaged area within a field of view (FOV) determined by the physical collimation applied. During the rotation, many single, sequential planar projection images (from 150 to over 1,000) are acquired of the FOV in a complete rotation or partial arc of 180^0 or greater. These individual image projections constitute the raw primary data and are individually referred to as basis, frame or raw images (Fig. 1). The complete series of images is called the *projection data* (Fig. 2). This digital data is reconstructed to create a 3-D volumetric dataset composed of cuboidal isotopic volume elements (voxels) by a sequence of software algorithms in a process called primary reconstruction (Fig. 2).[5,7,9–11] Subsequently, visual orthogonal (i.e. perpendicular images in all three planes) sectioning the volumetric dataset is provided, referred to as *secondary reconstruction* (Fig. 3).

Equipment Configurations

There are many manufacturers offering CBCT imaging devices each with several unit configurations.[3,8] Units can be distinguished operationally according to the orientation of the patient during image acquisition

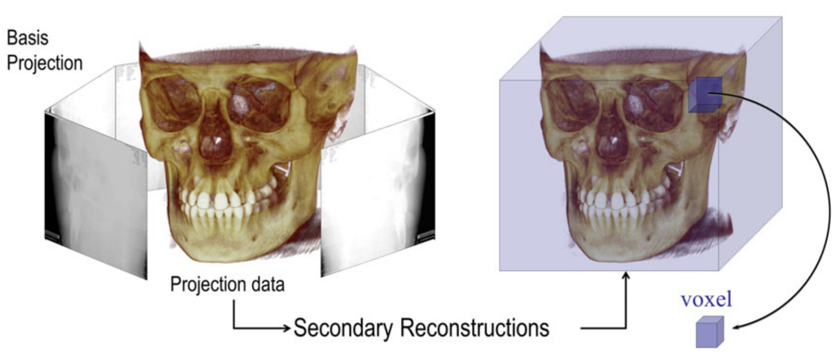

Fig. 2 In CBCT, a single complete or partial rotation produces a series of multiple, slightly off-set 2D flat planar basis projection images of the object which together comprise the projection data. Secondary reconstruction of the projection data by software algorithms provides a volumetric dataset comprised of voxels. Because CBCT data acquisition is dependent on the pixel size of the area sensor the voxels are equal in all three dimensions (isotropic) rather than columnar (anisotropic).

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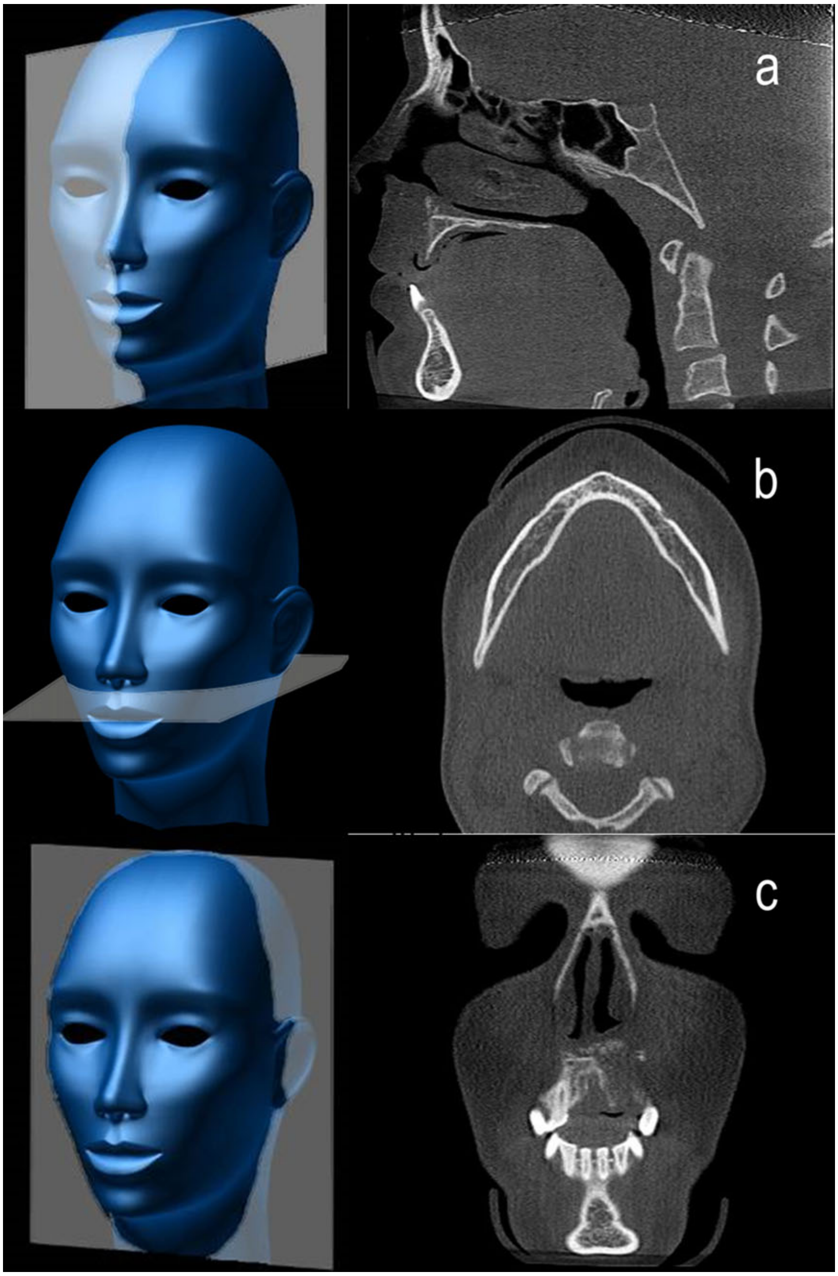

Fig. 3 Secondary reconstruction of CBCT projection data provides a volumetric dataset. The default display of a dataset are as contiguous uniform image sections in three perpendicular (orthogonal) planes - sagittal (a), axial (b) and coronal (c).

or imaging functionality. Most CBCT units scan the patient in either a standing and/or sitting position. A few are available in which the patient is scanned in the supine position (Fig. 4). CBCT systems can also be divided into stand-alone or hybrid multi-modal systems which combine digital panoramic and/or cephalometric radiography with a small to medium-FOV CBCT system (Fig. 4)

Technique

The operation of CBCT equipment is technically simple and operationally similar, in some respects, to panoramic radiography. However, most CBCT units provide numerous choices in available exposure settings. Appropriate selection of these parameters is necessary to optimise image quality and minimise radiation exposure according to the ALARA (As Low As Reasonably Achievable) or ALAP (As Low As Practical) principle.[12, 13] CBCT units are manufactured with "fixed" exposure settings or allow "manual" adjustment of kilovoltage (kVp) and/or milliamperes (mA). Adjustment should be based on the relative size of the patient and in compliance with the manufacturer's recommendations. The total number of basis images comprising the volumetric dataset may be fixed on some

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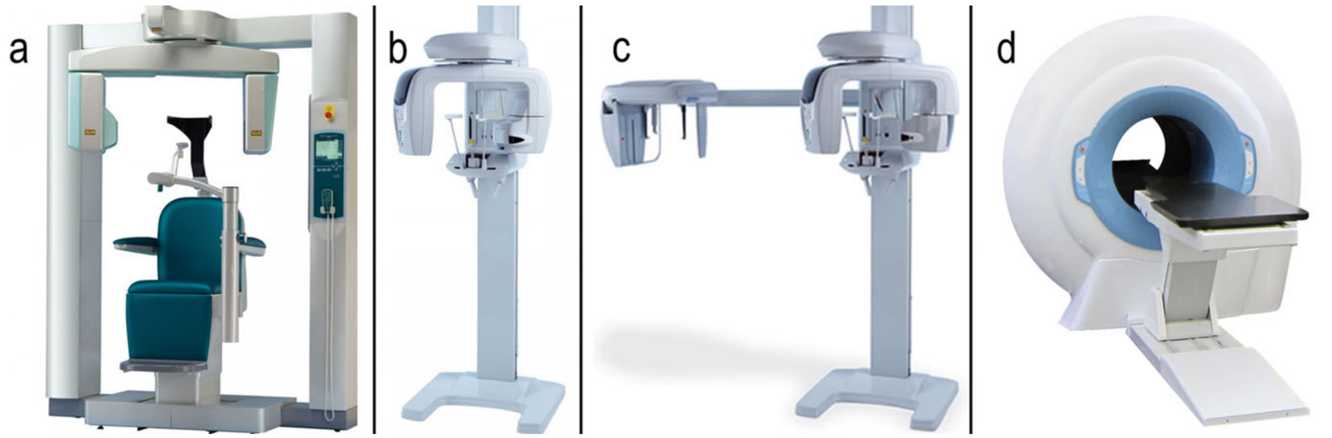

Fig. 4 Comparison of types of CBCT devices. According to function CBCT devices can be considered as dedicated units (e.g. 3D Accuitomo 170, J Morita Corp., Osaka, Japan) (a), a hybrid unit with panoramic capabilities (e.g. Veraviewepocs 3D F40 (J Morita Corp., Osaka, Japan) (b) and, hybrid unit with panoramic and cephalometric modalities (e.g. Veraviewepocs 3D R100, J Morita Corp., Osaka, Japan) (c). CBCT devices can also be divided by the position of the patient during the scan as seated (a), standing (b and c) or supine (d) (e.g. Newtom 5G, QR srl, Verona, Italy) units.

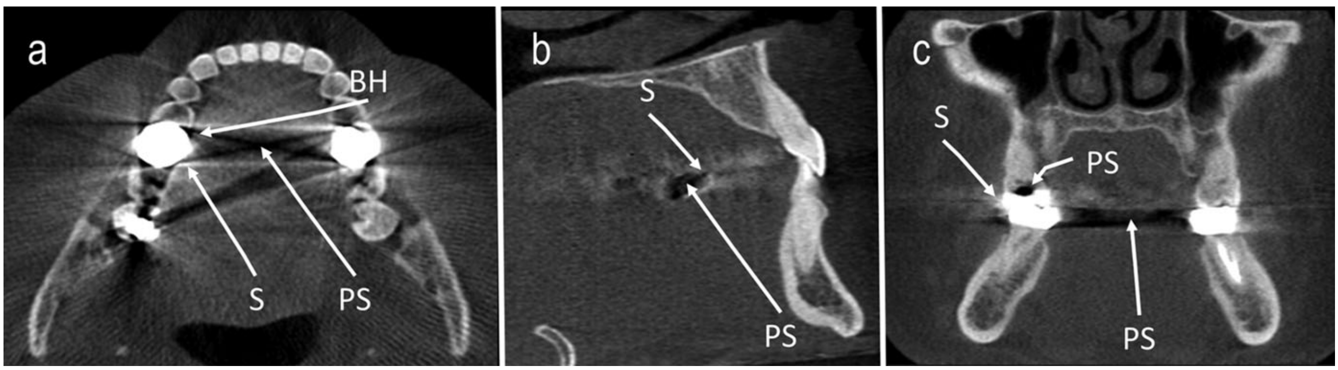

Fig. 5 Axial (a), sagittal (b) and coronal (c) thin section images demonstrating scatter (S - white streaks), beam hardening (BH - dark streaks), and photon starvation (PS - black voids) CBCT artifacts.

Table 1. Summary of Published Adult Effective Doses (E)* for Various Radiographic Examinations in Orthodontics[22]

Radiographic Examination	Procedure	E		Comparative Dose	
		Mean ± SD	Range	Digital panoramic image	Per capita background (Days)†
Extraoral	Pano‡	16.1	12–38	1	2
	LC§	4.5	2–5.6	0.3	0.6
	PA¶ LC	5	NA#	0.3	0.6
CBCT**	Mx†† FOV_s	53 ± 38	5–140	3.3 ± 2.4	6.7 ± 4.6
	Mn‡‡ FOV_s§§	102 ± 88	18–488	6.3 ± 5.5	14.4 ± 10.7
	FOV_m¶¶	177 ± 137	47–560	11 ± 8.5	21.6 ± 16.6
	FOV_l##	212 ± 212	46–916	13.2 ± 13.2	25.8 ± 25.8

Note: Only averages are provided based upon a limited number of phantoms and calculations that may not necessarily represent doses received by any actual person for any given diagnostic task or reflect that required to achieve diagnostic image quality
*In microsieverts.
†Based on an annual full body exposure of 3 mSv (Source: Valentin.[21])
‡Pano: rotational panoramic radiography
§LC: lateral cephalometric radiography
¶PA: postero-anterior
#NA; not available
**CBCT: cone beam computed tomography
††Mx: Maxilla
‡‡Mn: Mandible
§§FOV_s: Small FOV with a spherical volume diameter or cylinder height < 10 cm
¶¶FOV_m: Medium FOV with a spherical volume diameter or cylinder height ≥10 cm and <15 cm;
##FOV_l: Large FOV with a spherical volume diameter or cylinder height ≥15 cm.

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devices and variable on others. A greater number of basis images provides more information to reconstruct the image and generally produces images with better contrast, decreased graininess or noise, "smoother" images, and potentially less metallic artifact. However, an increase in time of the scan produces a proportionately higher patient dose and a longer primary reconstruction time.

CBCT devices may allow for adjustment of various projection geometry parameters including spatial resolution, rotation arc and FOV. Tasks requiring high spatial resolution in orthodontics (e.g. determining if an unerupted tooth is ankylosed or if a tooth root surface has external resorption) should be performed at a voxel resolution of 0.2 mm or finer. Depending on the unit, the choice of lower resolution may result in a reduced patient radiation dose.[14] Some units have a variable rotation arc while others are fixed. The rotation arc may be complete or limited (< 360^0). Images obtained with CBCT units with a reduced rotation angle have greater noise and suffer from additional artifacts; however, the patient radiation dose is reduced. Only a few CBCT units now have a fixed FOV. The FOV should be adjusted to cover only the

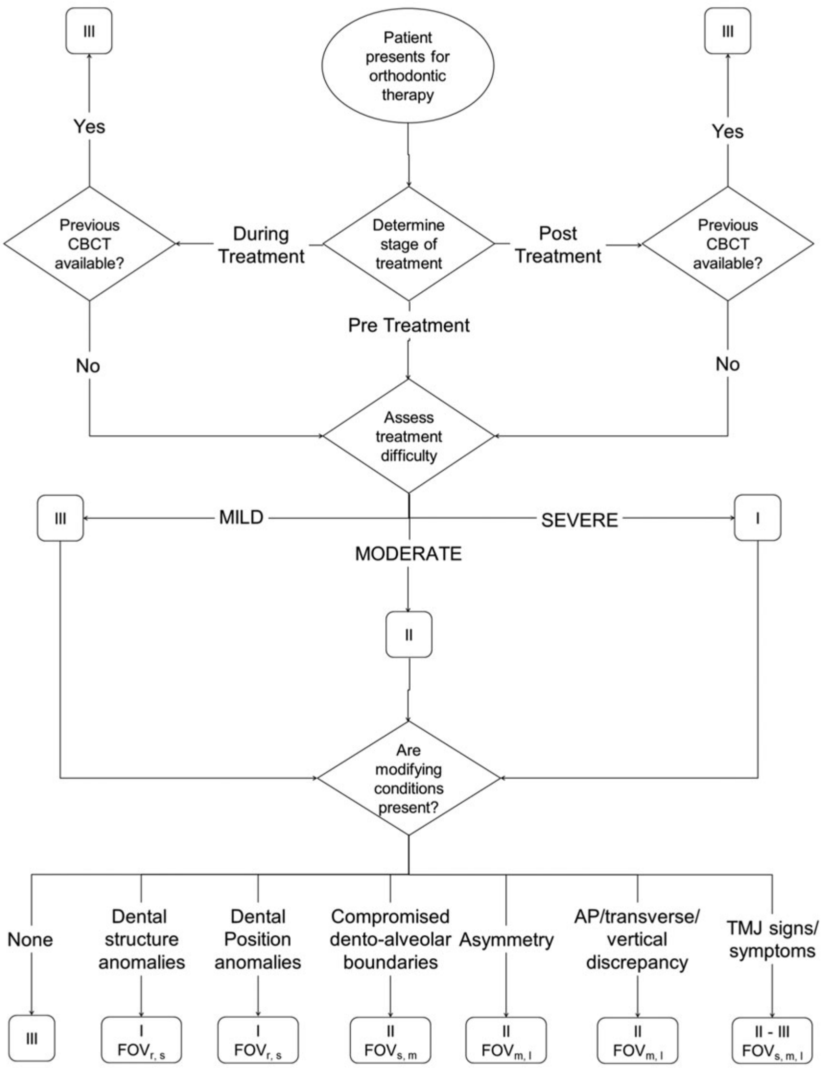

Fig. 6 Summary of the Recommendations for Appropriate Selection of CBCT imaging in Orthodontics (American Academy of Oral and Maxillofacial Radiology, 2013) At initial presentation, the first decision is to determine the phase of treatment (pre-, during, or post-treatment). If the patient is undergoing treatment or is post-treatment, then if a previous CBCT scan is available, then a second is likely not indicated (III). If unavailable, the potential treatment difficulty should be determined as Mild (dental malocclusions, with or without minimal anterior-posterior, vertical, or transverse skeletal discrepancies), Moderate (dental and skeletal discrepancies that are treated orthodontically and/or orthopedically only including bimaxillary proclination, open bite, and compensated Class III malocclusion) or severe (skeletal conditions including, but not limited to complicated skeletal discrepancies, craniofacial anomalies such as cleft lip and palate and craniofacial synostosis, obstructive sleep apnea, speech disorders, and post-surgical/trauma). For mild difficulty patients, CBCT is likely not indicated (III), for moderate difficulty patients CBCT may be indicated in certain circumstances (II) and for severe treatment difficulty patients CBCT is likely indicated (I). Finally, CBCT of various fields of view (FOV) are most likely (I) or possibly indicated in certain circumstances (II) with the presence of additional skeletal and dental conditions. (FOV_l, Large; FOV_m, Medium FOV; FOV_s, Small FOV; FOV_r, reduced FOV)

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region of interest (ROI). As a trend for the same CBCT unit, the larger the FOV, the greater the effective dose to the patient. However, comparable FOV on different CBCT units produce a range of radiation exposures.

Limitations

CBCT images have inherent "noise" that reduces image clarity and produces limited soft tissue contrast resolution. CBCT image quality is also affected by image artifacts such as streaking, shading, rings, and distortion due to high areas of attenuation (such as metallic restorations) (Fig. 5) and inherent spatial resolution may limit adequate visualisation of structures in the dento-alveolar region.

Dose and Risk Considerations in Orthodontics

CBCT imaging uses ionising radiation which is a potential carcinogen. Recent public[15] and scientific reports[16–18] have increased public awareness and professional concerns over the potential association between diagnostic radiation exposure and cancer. The use of any radiographic technique demands that each patient exposure be justified clinically and that principles and procedures are applied that minimise patient radiation exposure while optimising maximal diagnostic benefit. The extension of this principle, referred to as the "as low as reasonably achievable" (ALARA)[13] to CBCT imaging is supported by professional organisations[19] and Australian government agencies.[20]

Effective dose (E), reported in Sieverts (Sv), is used to calculate whole-body dose and is the currently

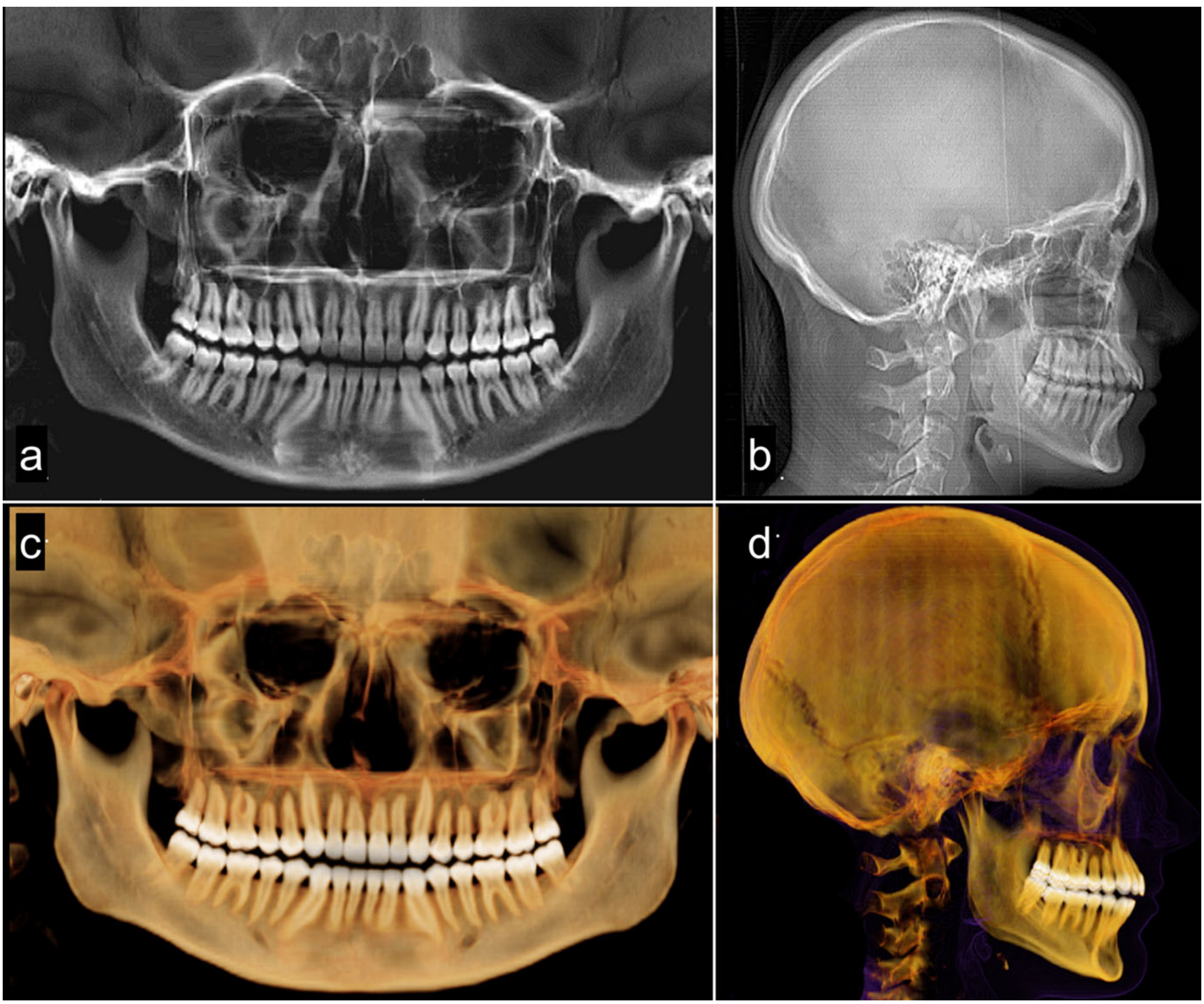

Fig. 7 Example of simulated projection panoramic (a) and lateral cephalometric (b) radiographic and comparable 3D volumetric panoramic (c) and lateral (d) images generated from CBCT data.

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accepted index of radiation dose risk from exposure to ionising radiation. E is a weighted total, based on relative susceptibility, of the absorbed dose within specific tissues and organs.[21] Currently, E does not take into consideration patient susceptibility variations such as gender and age. The actual risk for low-dose radiographic procedures, such as maxillofacial radiography including CBCT, is difficult to assess and is based on

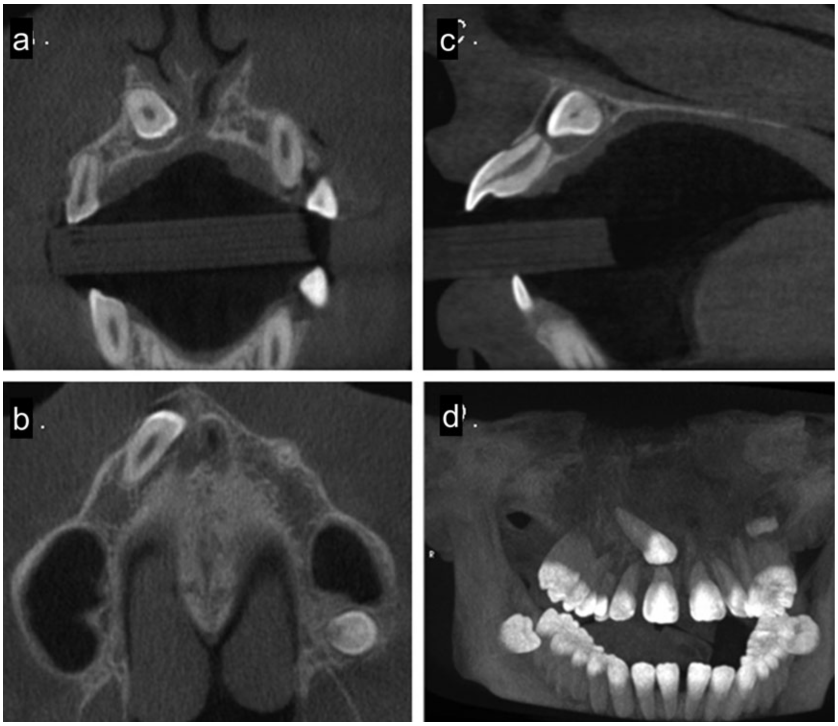

Fig. 8 Coronal (a), axial (b), and sagittal (c), inter-relational, undistorted orthogonal images showing the orientation of an unerupted impacted ectopically-positioned, maxillary right canine and apical root resorption of the adjacent central incisor. The maximum intensity projection (MIP) (d) provides a translucent "glass-like" image clearly showing the location, orientation and relationship of the canine to the erupted teeth.

Table 2. Indications and Specific Conditions for the Use of CBCT in Orthodontics

Indication	Specific Conditions	Example
Dental structural anomalies	Variations in tooth morphology	Fusion, gemination, dens on dente, dilacerated roots and transposed roots
	Variations in tooth size	Macrodontia, microdontia such as peg-shaped maxillary lateral incisors,
	Variations in tooth number	Oligodontia, hypodontia such as congenitally missing maxillary lateral incisors, and hyperdontia including supernumerary teeth (Fig. 10)
	Localized or generalized structural variations	External and internal root resorption, congenital conditions affecting the entire dentition [e.g. amelogenesis imperfect].
Anomalies in dental position	Impacted teeth	Third molars or maxillary canines (Fig. 11), unerupted and impacted supernumerary teeth such as mesiodens (Fig. 10)
	Anomalies in dental eruption sequence	Jaw clefts, ectopic eruption
Dento-alveolar morphology	Localized defects	Fenestrations and dehiscence
	Alveolar width	Facio-palatal/lingual boundaries for orthodontic torque movement of teeth (Fig. 12), alveolar clefts, implants, bone grafts, or temporary anchorage devices
Dentofacial deformities and craniofacial anomalies	Skeletal discrepancies	Facial (Fig. 13) or mandibular asymmetry, Class II and Class III skeletal malocclusions (Fig. 14), vertical and transverse deficiencies
The temporomandibular joint	Developmental conditions	Positional changes, condylar hyperplasia, hypoplasia or aplasia, previous condylar trauma (Fig. 15).
	Pathologies	Osteoarthritic degeneration, tumors
Post-therapy assessment	Non-surgical	Nonsurgical devices to affect vertical or transverse discrepancies (Fig. 16), airway post therapy changes
	Surgical	Orthognathic surgery, grafting procedures
Airway	Obstructive sleep apnea/hypopnea syndrome	Localization of airway obstructions, retro-pharyngeal and retroglossal airway reductions (Fig. 17)
Pathology	Jaw	Infections (Fig. 18), benign cysts and tumors
	Sinus	Rhinosinusitis, intrinsic cysts and tumors

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conservative assumptions as there are no data to establish the occurrence of cancer following exposure at these levels. However, it is generally accepted that any increase in dose, no matter how small, results in an incremental increase in risk.[21] Therefore, there is no safe limit or "safety zone" for radiation exposure in orthodontic diagnostic imaging. Every exposure cumulatively increases the risk of cancer induction.

The risk associated with various dental radiographic procedures, specifically CBCT imaging, has most often been compared to the radiation dose imparted by a "baseline" imaging modality (e.g. typical panoramic radiographic procedure) or to average background equivalent radiation time (e.g. days of background) (Table 1). In orthodontics, exposure to ionising radiation from CBCT imaging is of particular concern because it involves imaging predominantly younger individuals:

- Almost all CBCT units impart higher doses than the range reported from digital panoramic, lateral cephalometric, or four-image bitewing intraoral radiography (Table 1).[22]
- Younger patients are more radiosensitive than adults (i.e., the cancer risk per unit dose of ionising radiation is higher for younger patients).[23]
- Younger patients have a longer expected lifetime for the effects of radiation exposure to present as cancer.
- Organ doses, particularly the salivary glands, and effective doses for children with CBCT are, on average, 30% higher than for adolescents with the same exposure.[24]
- A course of orthodontic therapy often incorporates multiple radiographic examinations so cumulative CBCT dose over time should be considered.

Because of these considerations, children may be two to ten times more sensitive to radiation

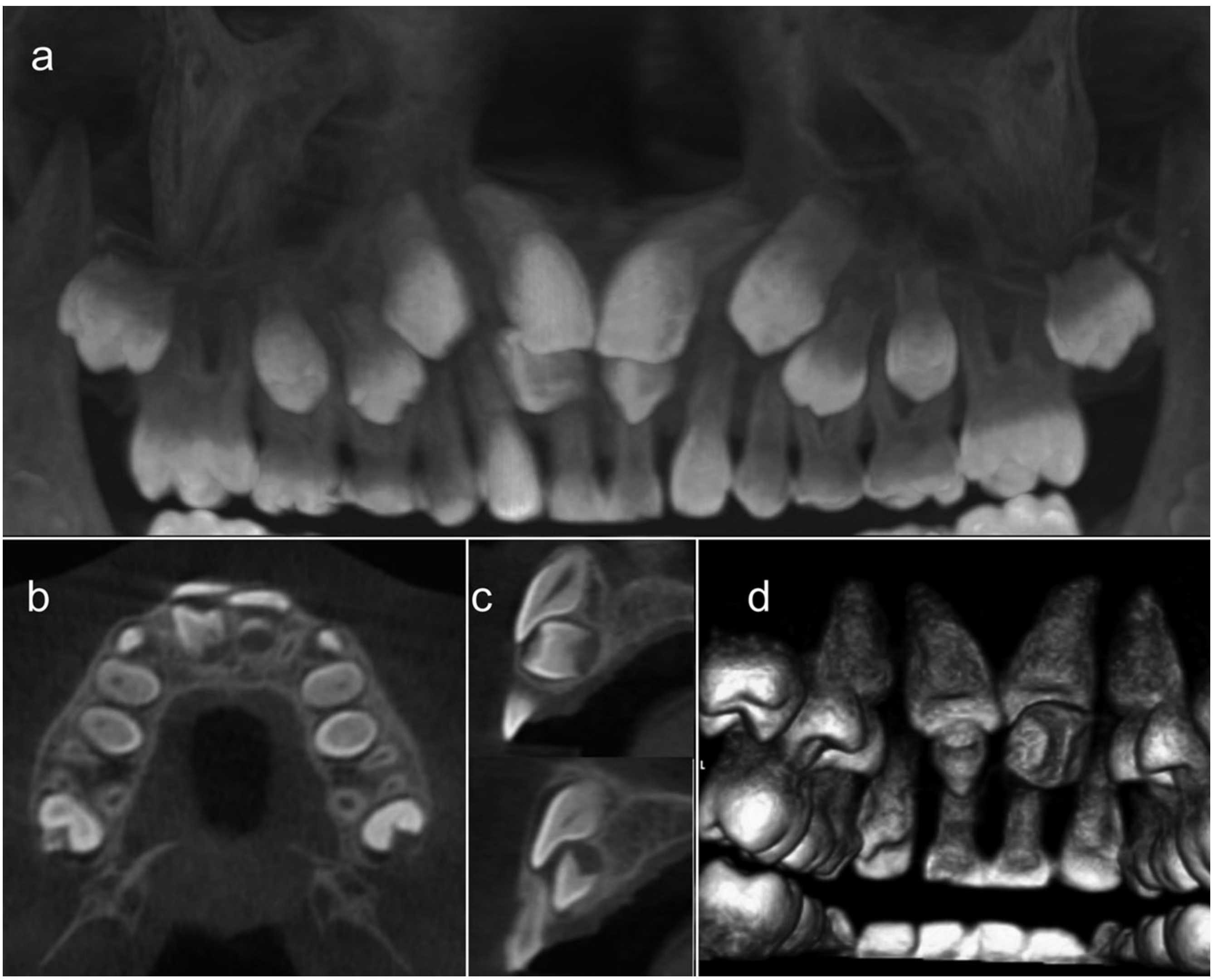

Fig. 9 Reformatted panoramic (a), axial (b), cross-sectional (c) and 3D virtual model (d) demonstrating location and position of two maxillary supernumerary teeth preventing the eruption of and displacing the maxillary central incisors labially.

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carcinogenesis than mature adults.[25, 26] This translates to a mortality risk to children of three to five times that of adults for the same exposure.[23]

There are numerous methods to reduce the radiation exposure to patients when CBCT imaging is used. The simplest is to reduce the field of view (FOV) of the CBCT unit to cover a specific region of interest by collimating the x-ray beam and therefore limiting the area of exposure. Exposure can also be minimised by the adjustment of exposure settings (kVp and mA),

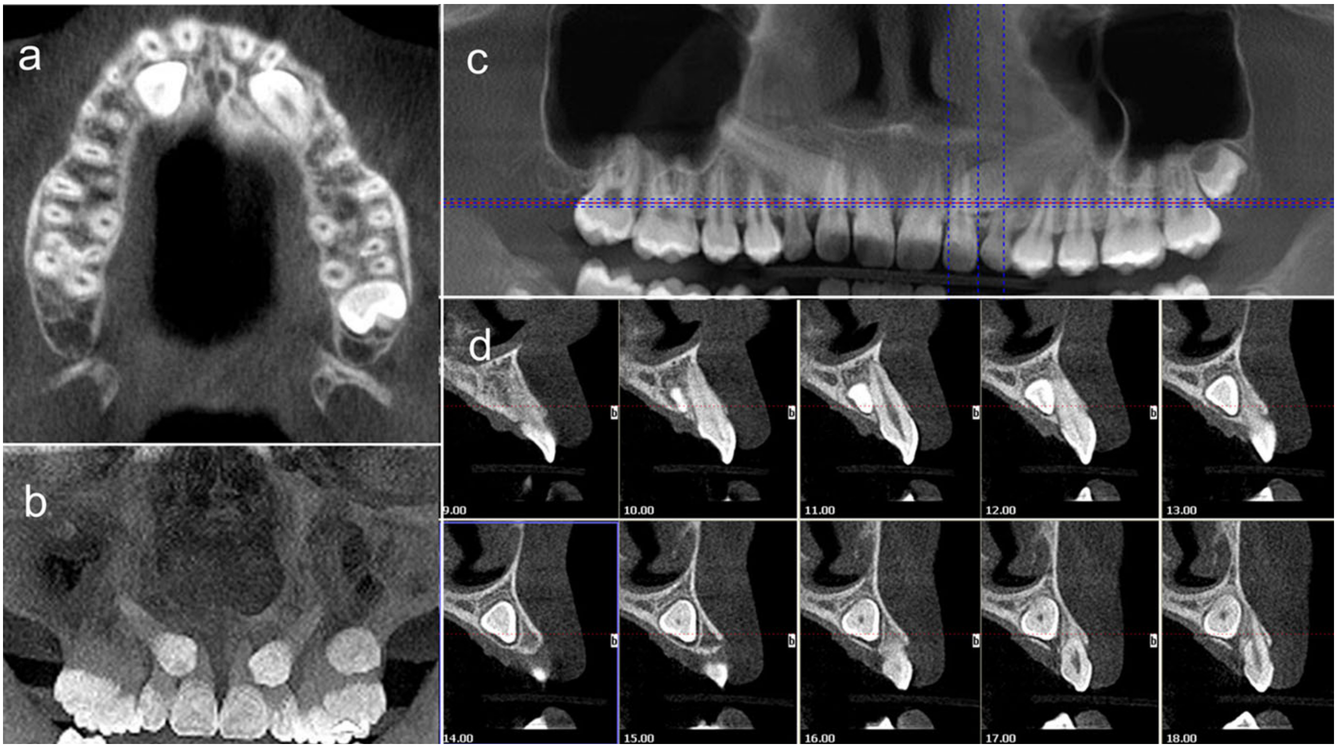

Fig. 10 Axial (a), frontal maximum intensity projection rendering (b), reformatted panoramic (c), and multiple cross-sectional 1mm thick sections (d) of the left anterior region demonstrating the location, orientation and position of severely mesio-angular, palatally-positioned, completely bony impacted and unerupted maxillary canines bilaterally.

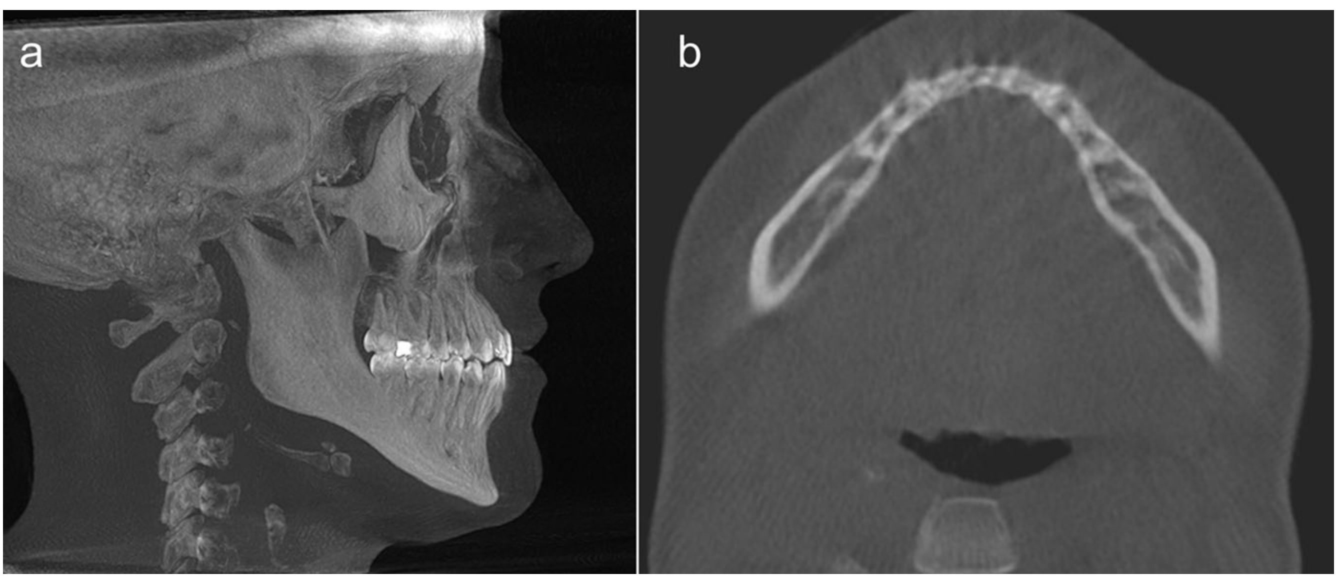

Fig. 11 Maximum intensity projection lateral cephalometric image reformatted from CBCT data (a) demonstrating anterior open bite and excessive inter-incisal angle between the maxillary and mandibular incisors requiring a change in the position of the anterior mandibular incisors. The axial image (b) shows a very thin alveolar bone width associated with the roots of the mandibular incisor teeth.

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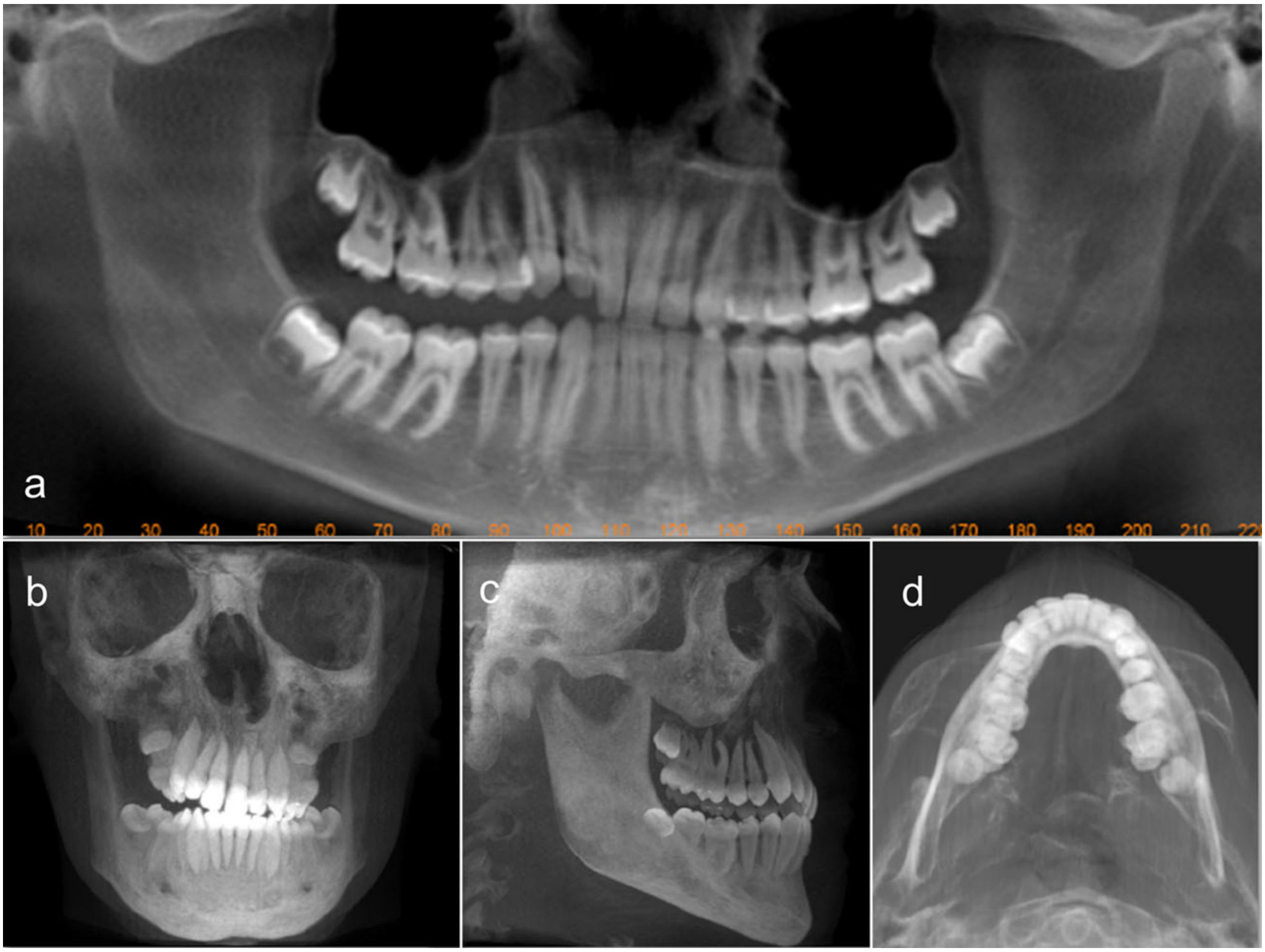

Fig. 12 Reformatted panoramic (a) and maximum intensity projection frontal (b), right lateral (c) and submento-vertex (d) renderings showing facial asymmetry with maxillary transverse deficiency and right vertical maxillary deficiency with severe right sided anterior and posterior open bite associated with right unilateral maxillary hypoplasia.

Fig. 13 Right lateral (a) and frontal (b) maximum intensity projections showing severe Class II skeletal with anterior open bite and high mandibular plane due to maxillary insufficiency.

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and a reduction in the number of basis projection images. Avoiding regions of high relative radiation risk (e.g. eyes and thyroid gland) can also reduce the risk to patients. The use of patient protective shielding such as lead torso aprons and thyroid shields is recommended, when possible, to minimise exposure to radiosensitive organs outside the field of view.

Recently, a number of manufacturers have introduced CBCT units capable of providing medium or even full FOV CBCT acquisition using “low dose” protocols. By adjustments to rotation arc, mA, kVp, or number of basis images or a combination thereof, CBCT imaging can be performed at effective doses comparable with conventional panoramic examinations (range, 14 μSv to 24 μSv)[22, 27–29] However, this is accompanied by significant reductions in image quality. Even at this level, child doses have been reported to be, on average, 36% greater than adult doses.[27] The use of low dose protocols may be adequate for low level diagnostic tasks such as root angulations. No data is currently available evaluating the effect of low dose protocols on the diagnostic accuracy of other orthodontic tasks such as degree of root resorption.

THE ROLE OF CBCT IMAGING IN ORTHODONTICS

As with all radiographic procedures in Dentistry, the use of CBCT in orthodontics should not be routine and should be considered only after a review of the patient’s health, availability of previous radiographs and the completion of a thorough clinical examination. For each patient, the potential benefits of the imaging series should be weighed against the known risks to justify the exposure.

Because of the ease with which CBCT scans can be performed, the introduction of “low dose” protocols and the attraction of finding some potentially important additional diagnostic information, some advocate that panoramic and lateral cephalometric radiography should be replaced by CBCT for standard orthodontic diagnosis and treatment.[30, 31] This is based on illustrative, but anecdotal, case reports without support of the current published evidence base. While there is no doubt that CBCT provides greater confidence in specific clinical orthodontic circumstances and provides additional diagnostic information (See *Specific Indications* to follow), there is growing, but limited, evidence

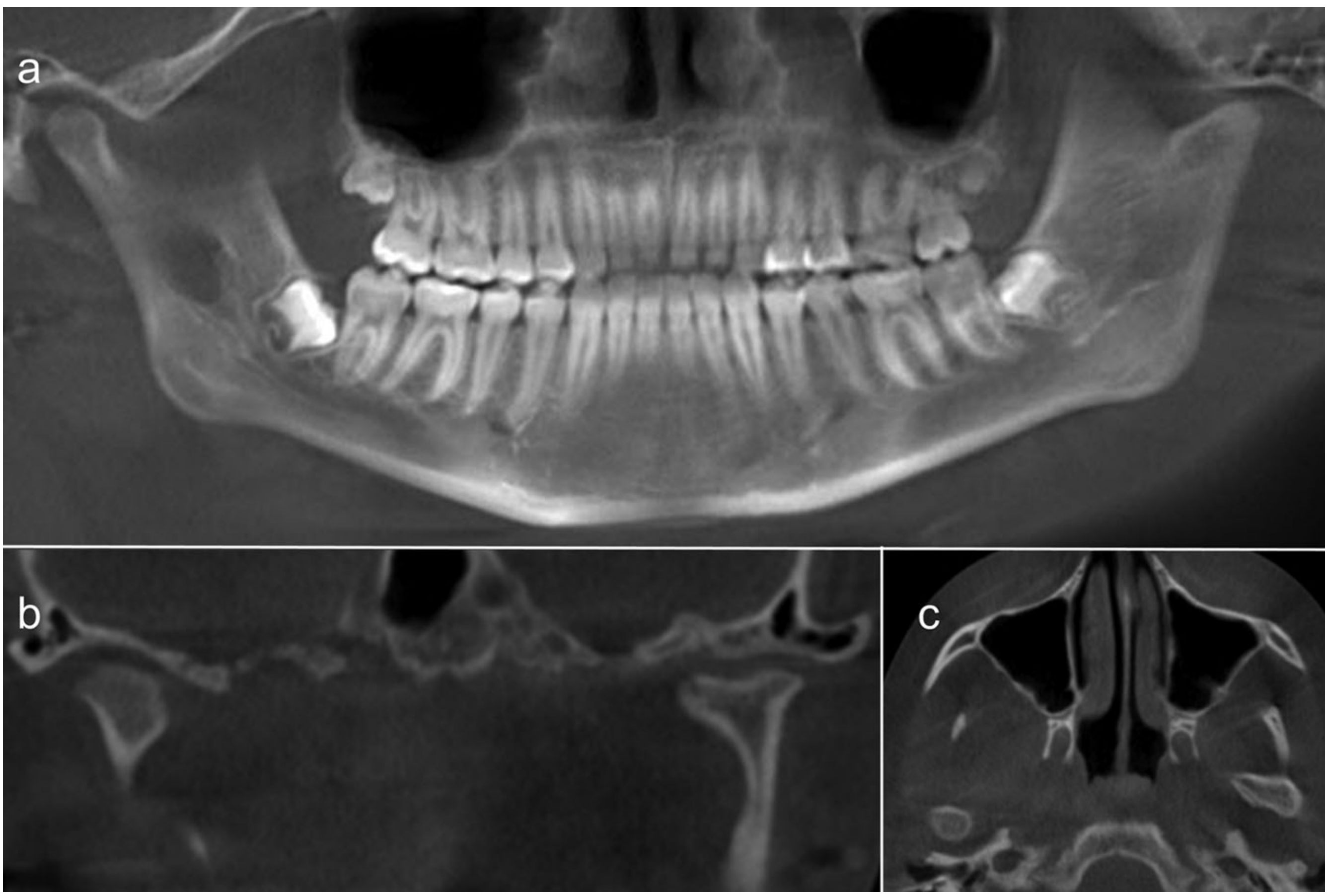

Fig. 14 Reformatted panoramic (a), 2mm orthogonal coronal (b) and axial (c) sections through the mandibular condyles showing left healed and remodeled condylar fracture. Note the remodeling of both the temporal glenoid fossa and mandibular condylar components such that there is no overall vertical discrepancy on the left side.

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that such information has a clinical impact to cause a change in treatment approach compared with conventional imaging for specific clinical scenarios.[32–36]

Guidelines for Use of CBCT in Orthodontics

Current recommendations from the American Dental Association Council on Scientific Affairs (ADA-CSA) state that CBCT imaging should be performed, "*only when they (sic. the dental practitioner) expects that the diagnostic yield will benefit patient care, enhance patient safety or improve clinical outcomes significantly*."[19] The ADA-CSA also indicate that, "*CBCT should be considered as an adjunct to standard oral imaging modalities.*"[19] In regard to the appropriateness of CBCT imaging in orthodontics, the ADA-CSA states, "*Dentists should use professional judgment in the prescription and performance of CBCT examinations by consulting recommendations from available CBCT guidelines and by considering the specific clinical situation and needs of the individual patient.*"[19]

The American Academy of Oral and Maxillofacial Radiology (AAOMR) recently provided clinical guidelines developed by a consensus panel of board-certified orthodontists and oral and maxillofacial radiologists for the use of CBCT in orthodontics based on an analysis of the available published evidence.[37] To assist clinicians with their choice, specific imaging selection guidelines are provided based on the stage of treatment on initial presentation, potential treatment complexity and the presence of modifying factors.[37] For various clinical scenarios, an index of the strength of the current available evidence and

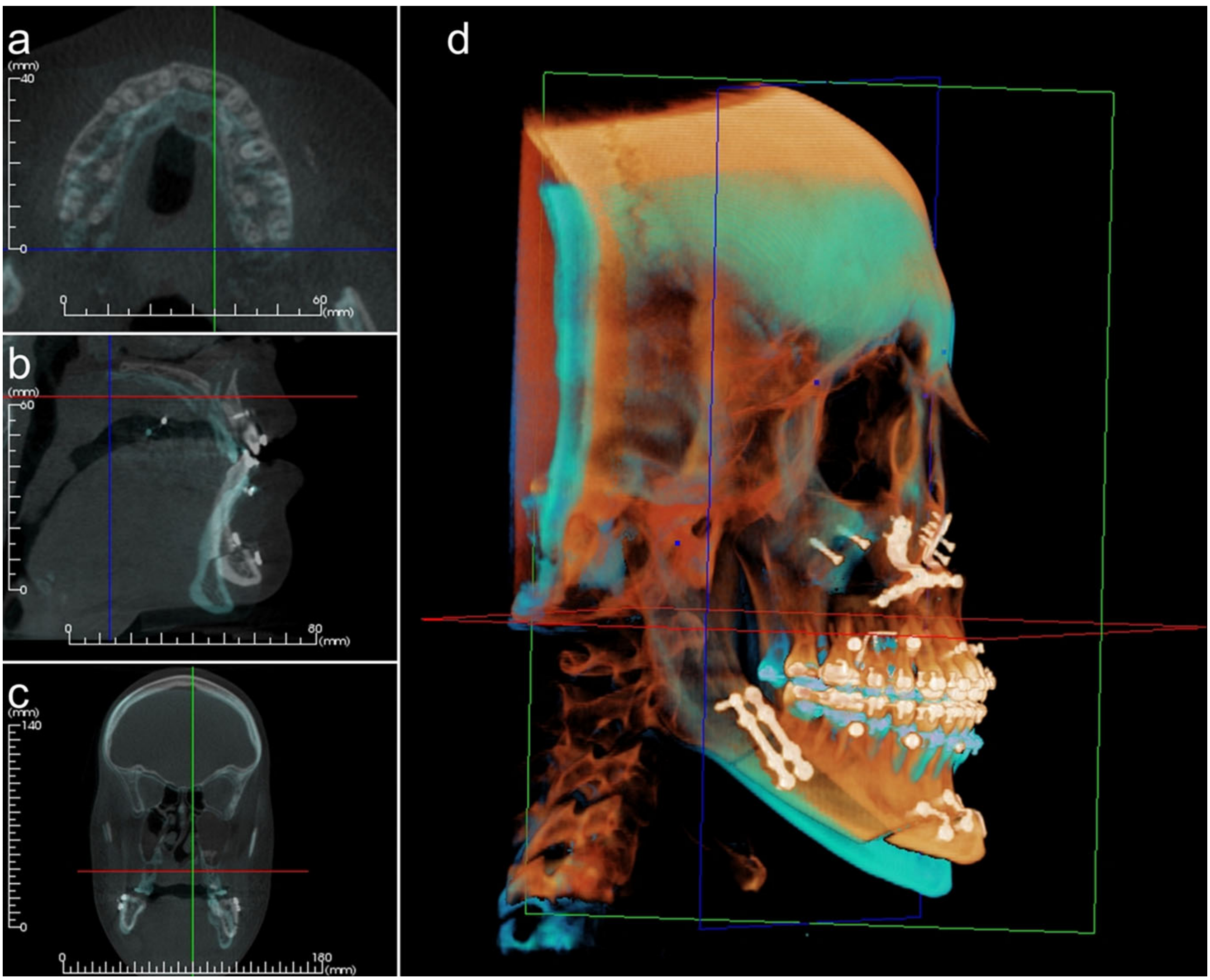

Fig. 15 Screen shot of computer program allowing superimposition of initial CBCT data (blue) with post orthognathic treatment CBCT data (orange). Superimposition of reference anatomic landmarks in axial (a), sagittal (b) and coronal (c) reference planes provides a 3D volumetric representation (D.). (Images courtesy of Anatomage, San Jose, California, USA).

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recommendations on the most appropriate field of view (FOV) is provided (Fig. 6).

Advantages of CBCT Imaging in Orthodontics

CBCT imaging provides many unique features and advantages to orthodontic practice over conventional extraoral radiographic imaging.

- **Greater Clinical Imaging Efficiency.** Full field of view (FOV) CBCT imaging provides volumetric data acquisition of the entire maxillofacial skeleton in a single radiographic procedure. This data can be easily reformatted to provide simulated radiographic (e.g. lateral and posterior-anterior cephalometric, panoramic) or comparable volumetric images (Fig. 7) currently used in orthodontic diagnosis, cephalometric analysis, and treatment planning. This provides for greater clinical imaging efficacy. However, this level of imaging may not be necessary, particularly in less complex situations.[38, 39]
- **Provides 3D Visualisation.** CBCT data can be reconstructed to provide unique, inter-relational, orthogonal (i.e. axial, sagittal and coronal) images previously unavailable for orthodontic assessment (Fig. 8). Other imaging processing can also be performed such as maximum intensity projection (MIP) and surface or volumetric rendering that provides an interactive volumetric model enabling visualisation and inter-relationship of craniofacial structures including the maxillofacial skeleton and soft tissue boundaries such as the airway and facial outline.
- **Anatomic Accuracy.** Unlike traditional extraoral and panoramic radiography, CBCT images and renderings are anatomically accurate and can be displayed at any angle for any part of the maxillofacial skeleton. Therefore, actual measurements can be

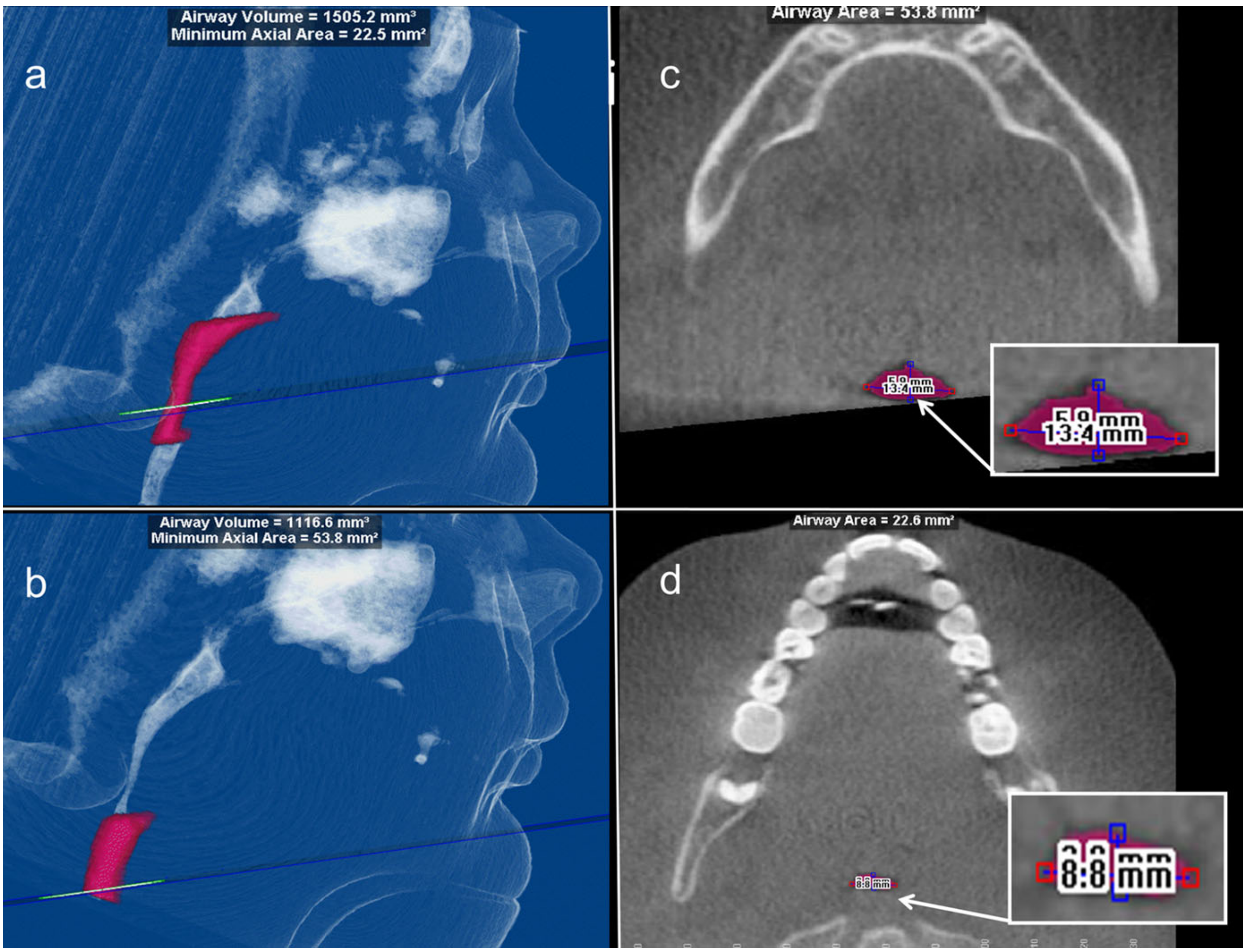

Fig. 16 Lateral 3D images of the segmented airway of a patient with OSA showing the segmented volumes of retroglossal (a) and retropalatal (b) airway space. The software algorithm identifies and displays the axial images at which the minimum cross-sectional area is present (c and d) and allows for measurement of antero-posterior and transverse dimensions (insert). (Images created using Dolphin 3D, Dolphin Imaging and Management Solutions Chatsworth, California, USA)

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obtained without the need for considerations of magnification or projection discrepancies.

- Clinical Indications. CBCT imaging is indicated for the assessment and diagnosis of a number of specific conditions in orthodontic patients (Table 2) (Figs. 9 to 17).[37, 40]
- **Data Integration.** Orthodontics and orthopaedics involves considerations of the maxillofacial skeleton, the dentition and soft-tissue integument – the facial mask. CBCT data can be used as a platform onto which other inputs can be fused with acceptable clinical accuracy. These data sources include light-based surface data such as photographic facial images (Fig. 18) or high resolution surface models of the dentition produced by direct scans intraorally or indirectly by scanning impressions or study models. The integration of hard and soft tissues can provide a greater understanding of the inter-relationship of the dentition and soft tissues to the underlying osseous frame.
- **3D Cephalometry.** The DICOM (Digital Imaging and Communications in Medicine) file format standard allows importation of CBCT data into third party software capable of accurate visualisation of the dataset and volumetric 3D cephalometric analysis (Table 3).[41] The effects of therapy, particularly orthognathic surgery, can be reviewed by superimposition of volumetric 3D images.[42, 43] Because of the time necessary to perform the analysis, high cost of the software program, and limited evidence for the diagnostic efficacy of this approach,[44] the application of 3D cephalometry is currently limited to

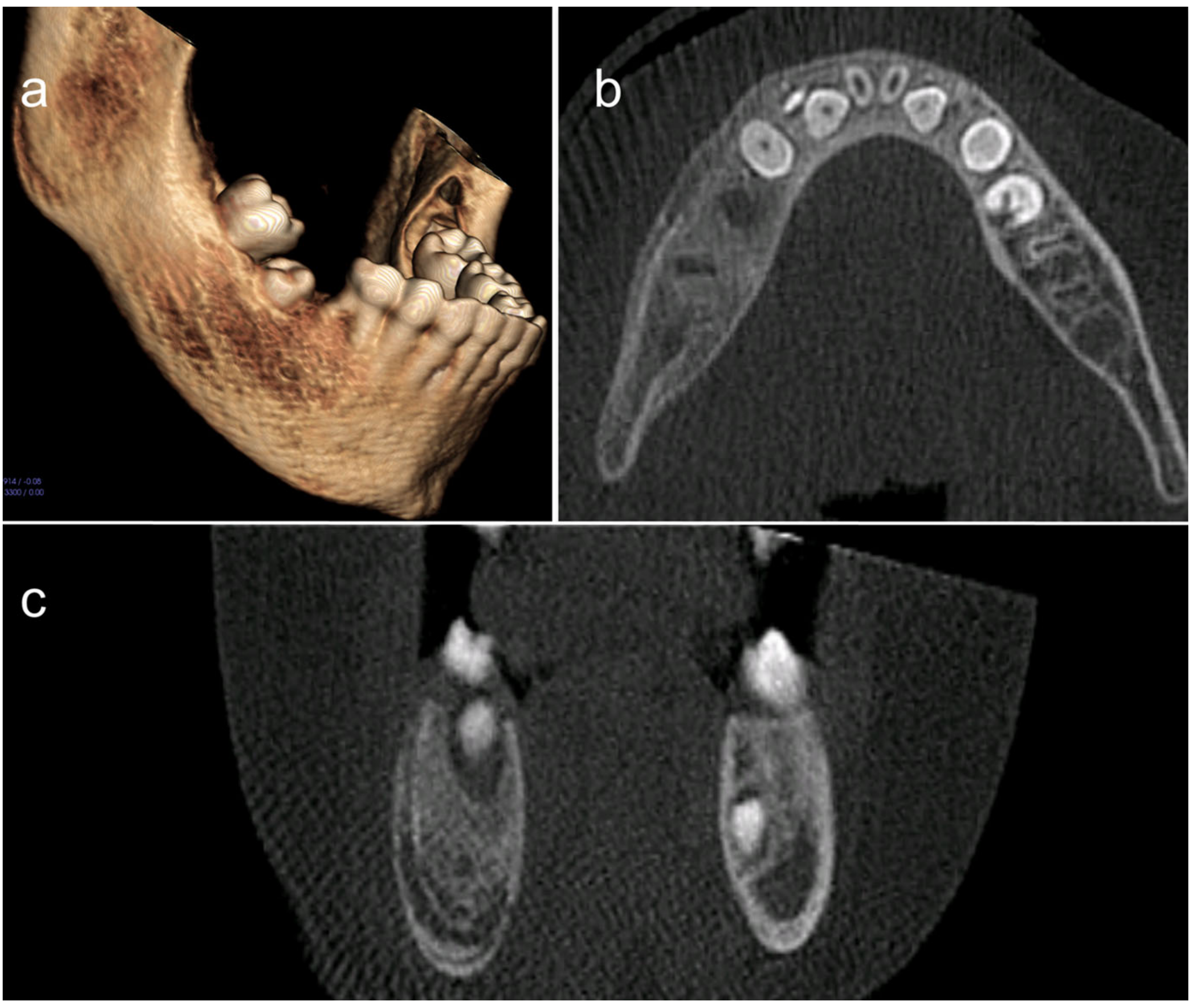

Fig. 17 Volumetric 3D rendering (a), axial (b) and, coronal (c) images of a young patient with expansion of the right mandibular body and pain after removal of an infected deciduous tooth with failure of eruption of the second premolar. The regional intra-medullary sclerosis and "onion-skin" cortical laminations are suggestive of Garres osteomyelitis with proliferative periostitis.

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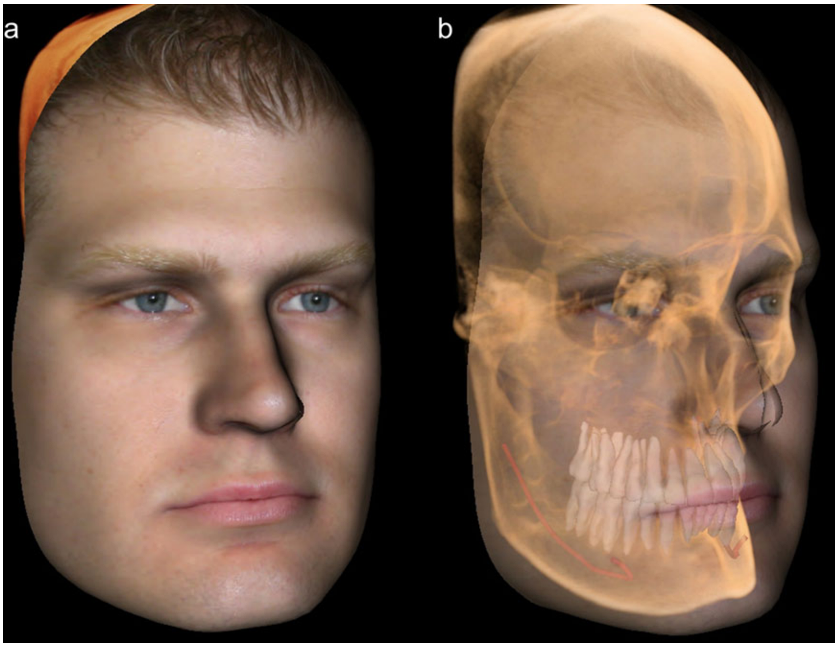

Fig. 18 Lateral oblique profile 3D volumetric patient composite (a) from integration of surface photograph (a) and CBCT data (b) (Images courtesy of Anatomage, San Jose, California, USA).

Table 3. Examples of 3D orthodontic display and analysis software

Software	Manufacturer
3dMD Vultus	3dMD, Atlanta, Georgia, USA
Dolphin 3D	Dolphin Imaging, Chatsworth, California, USA
InVivoDental	Anatomage, San Jose, California, USA
ACRO 3D	Cliniques universitaires Saint-Luc- Université Catholique de Louvain
ViewBox4	dHAL software, Kifissia, Greece
Beta NemoStudio	Software Nemotec SL, Madrid, Spain
Maxilim	Medicim, Nobel Biocare, Mechelen, Belgium
MIMICS	Materialise, Belgium
CMF application software	M.E. Müller Institute for Surgical Technology and Biomechanics, University of Bern, Switzerland
3DSlicer CMF	http://www.slicer.org[41]

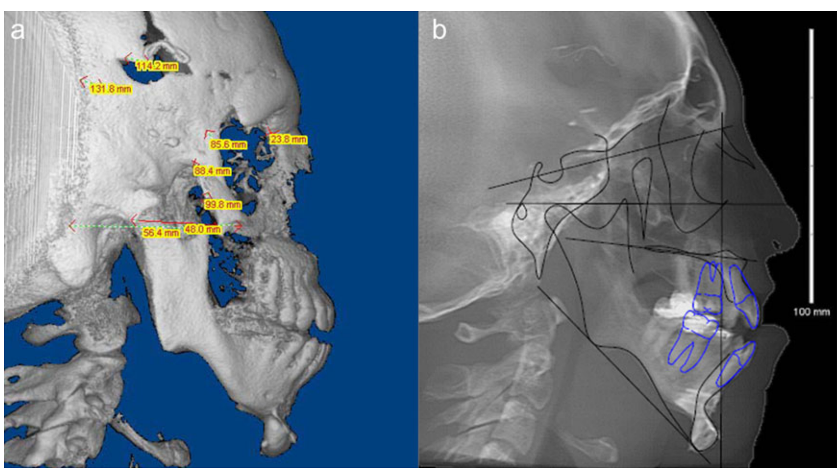

Fig. 19 Lateral volumetric shaded surface rendering (a) with 3D cephalometric measurements of patient with corrected craniofacial deformity and comparable lateral cephalometric image with tracing (b) both created from CBCT data. (Images created using Dolphin 3D, Dolphin Imaging and Management Solutions Chatsworth, California, USA)

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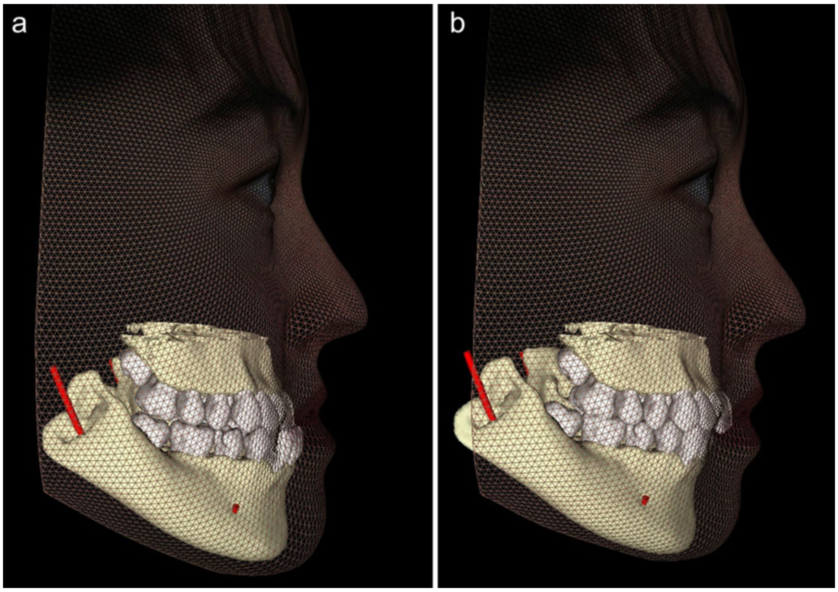

Fig. 20 Pre-surgical facial surface image integrated with CBCT derived virtual models of the jaws with highlighted mandibular neurovascular contents (a) shows the effect of Class III skeletal relationship to the dental profile. Predictive orthognathic virtual surgery of the 3D models shows the predicted effect on the facial profile (b). (Images courtesy of Anatomage, San Jose, California, USA).

the pre-surgical and post-operative analysis of patients with complex maxillofacial abnormalities.

- **Virtual 3D Models.** Most orthodontic software programs can be used to create accurate virtual 3D models of the maxillofacial region (Fig. 19).[45–47] However, the separation of bony or tooth structures from the volumetric dataset, referred to as *segmentation*, is a time-consuming technique, prone to artifacts and may result in clinical levels of inaccuracy of 3D surface models particularly in regions of thin bone such as the condylar region and lingual cortex of the mandible.[48, 49]
- **Predictive Simulations.** A virtual 3D VTO (Visual Treatment Objective) is a predictive computer-assisted simulation using CBCT data to provide a pictorial digital 3D representation of the optimal post-therapy treatment result based on virtual repositioning of either dental and/or maxillofacial skeletal components (Fig. 20). Establishing a VTO is important in that it facilitates a decision on proposed treatment feasibility, optimises case management and increases the patient's understanding and acceptance of the proposed treatment. However, soft tissue response to these movements, especially involving the skeletal envelope or facial mask, is simulated by software based on preprogrammed hard-to-soft tissue ratios which differ between available programs. Proprietary dental software for treatment simulations for both tooth (e.g. AnatoModel, Anatomage, Inc. San Jose, CA) and skeletal conditions for CBCT data are available and are highly reliable.

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