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Cutting Edge Review

The use of CBCT in orthodontics with special focus on upper airway analysis in patients with sleep-disordered breathing

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Abstract

Applications of cone-beam CT (CBCT) in orthodontics have been increasingly discussed and evaluated in science and practice over the last two decades. The present work provides a comprehensive summary of current consolidated practice guidelines, cutting-edge innovative applications, and future outlooks about potential use of CBCT in orthodontics with a special focus on upper airway analysis in patients with sleep-disordered breathing. The present scoping review reveals that clinical applications of CBCT in orthodontics are broadly supported by evidence for the diagnosis of dental anomalies, temporomandibular joint disorders, and craniofacial malformations. On the other hand, CBCT imaging for upper airway analysis—including soft tissue diagnosis and airway morphology—needs further validation in order to provide better understanding regarding which diagnostic questions it can be expected to answer. Internationally recognized guidelines for CBCT use in orthodontics are existent, and similar ones should be developed to provide clear indications about the appropriate use of CBCT for upper airway assessment, including a list of specific clinical questions justifying its prescription.

Keywords: cone-beam computed tomography; orthodontics; airway obstruction; obstructive sleep apnoea; diagnostic imaging.

Introduction

Background

Cone-beam CT (CBCT) imaging is based on an X-ray beam with conical shape that originates from a source performing a circular rotation, and uses a flat panel detector with a three-dimensional (3D) reconstruction algorithm.[1] CBCT imaging is available since the end of the 1990s,[2] and guidelines have been proposed for its application in dentistry by the European Academy of Dental and Maxillofacial Radiology[3] and by the Swiss Association of Dentomaxillofacial Radiology.[4] Furthermore, the British Orthodontic Society has reported about its specific use in orthodontics,[5] reserving special attention to children (Table 1).[6] About a decade ago, CBCT imaging was suggested for the analysis of the upper airway.[7] Subsequent publications have investigated its reliability,[8] presented various segmentation techniques,[9] and used this technology for assessing treatment outcomes in patients with sleep-disordered breathing (SDB) (Table 2).[10] SDB refers to a wide spectrum of sleep-related conditions characterized by an abnormal respiratory pattern and/or decreases in oxyhaemoglobin saturation during sleep, which may range from benign snoring to obstructive sleep apnoea (OSA).[11] OSA is a specific disease that presents with recurrent events of partial or total cessation of the airflow through the airway, disrupting normal oxygenation, ventilation, and sleep continuity.[12] Despite the many diagnostic possibilities it provides, CBCT uses ionizing radiations that are related to cancer risk, especially for growing individuals.[13] Therefore, its application should be based on the principle of "*As Low As Diagnostically Acceptable being Indication-oriented and Patient-specific*" (ALADAIP),[14] and should not be routinely used. To reduce harm, CBCT settings can be adjusted and low-dose protocols have been suggested for orthodontic applications.[15] For example, large field of view (FOV) low-dose protocols have been proposed for cephalometric analysis, with an effective dose of about 16 μSv.[15] On the other hand, the FOV should be reduced as much as possible based on the diagnostic question, for example, to roughly 4×4 cm for visualizing an impacted canine.[16] Based on FOV size, CBCT scans taken for orthodontic purposes may include brain, eye lens, salivary glands, oral mucosa, bone marrow, and lymph nodes, each of which deserves specific radiation-induced risk

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Table 1. Indications for the use of CBCT for orthodontic applications (representing a synthesis of the literature discussed in the respective section of the present review[22-73] and a consensus of the authors of this article).

Assessment	Query example	Application example	FOV*	Resolution*	Indication
Dental anomalies (Consider 2D X-rays as first-line assessment tool)					
	Impacted third molar	Extraction of impacted third molar with proximity to alveolar nerve	+	++ to +++	Green
	Impacted canines	Orthodontic extrusion/ extraction of bilaterally impacted canines	++	++	Green
	Dental agenesis	Distribution of multiple dental agenesis of one jaw	++ to +++	+	Yellow
	Presence and anomalies of supernumerary teeth	Orthodontic extrusion/ extraction of single supernumerary tooth	+	++	Green
	Dentoalveolar trauma	Dental root fracture	+	++ to +++	Green
	Dental root resorption	Root resorption of lower incisors after orthodontic distalization	+ to ++	++ to +++	Yellow
	Dentigerous cysts	Dentigerous cyst surgery	+	++ to +++	Green
TMJ disorders (Consider MRI as first-line assessment tool)					
	Morphology of condyle, fossa, and articular eminence	Condylar erosion due to arthritis/arthrosis (monolateral assessment)	+	++ to +++	Yellow
	Expansive lesions	Multiple myeloma of the mandibular condyle (monolateral assessment)	++	++	Yellow
	Condylar asymmetry	Condylar hyperplasia/hypoplasia (bilateral assessment)	++	+	Green
	TMJ trauma	Condylar fracture (bilateral assessment)	++	++	Green
Craniofacial malformations (Consider MDCT as first-line assessment tool)					
	Cleft lip and palate	Alveolar bone defect morphology for bone grafting	+ to ++	++	Green
	Syndromic malformations	Orthognathic surgery in patient with Treacher Collins syndrome	+++	+	Yellow
	Non-syndromic malformations	Orthognathic surgery in patients with severe skeletal Class III	+++	+	Yellow
Treatment planning and outcome prediction/assessment					
	Superimposition with intra-oral scanning	Digital design of custom-made clear aligners	++	++	Red
	Superimposition with extra-oral scanning	Simulation of treatment outcomes on facial aesthetics	+++	+	Red
Skeletal growth (Consider hand-wrist X-ray as first-line assessment tool)	Cervical vertebral maturation	Skeletal growth staging for orthodontic mandibular functional appliances	++	+	Red
	Fusion of the sphenoccipital synchondrosis	Skeletal growth staging for orthodontic mandibular functional appliances	+ to ++	++	Red
	Midpalatal suture maturation	Midpalatal suture maturation staging for RME	++	++ to +++	Red

\+ = small/low; ++ = medium; +++ = large/high.
Green = good scientific support; yellow = questionable scientific support; red = little scientific support.
Abbreviations: FOV = field of view, MDCT = multi-detector CT, TMJ = temporomandibular joint, RME = rapid maxillary expansion.
*Symbols only represent the most common setting that may be used for the reported application example, and every clinical situation must be assessed individually.

estimation.[17] In this context, the use of CBCT for upper airway analysis should be considered with further caution,[18] as it needs FOVs extending even more caudally that may expose to radiation the cervical spine, thyroid, vocal cords, epiglottis, and lingual tonsils.

Aim

Given the rapidly evolving applications of CBCT in orthodontics, the aim of the present review was to provide a comprehensive and critical summary on the most recent scientific evidence. Consolidated practice guidelines, cutting-edge

Table 2. Indications for the use of CBCT for upper airway assessment (representing a synthesis of the literature discussed in the respective section of the present review[83-136] and a consensus of the authors of this article).

Assessment	Query example	Application example	FOV*	Resolution*	Indication
Nasal cavity (Consider NE as first-line assessment tool)	Septum deviation	Septoplasty	+ to ++	+ to ++	Green
	Turbinate hypertrophy	Turbinectomy	+ to ++	+ to ++	Green
	Nasal floor width, thickness, and bone characteristics	TADs-supported RME	+ to ++	++	Green
	Internal nasal valve width	DOME surgery	+	+ to ++	Green
Tonsils (Consider NE as first-line assessment tool)	Adenoid hypertrophy	Adenoids grading	+ to ++	+	Yellow
	Palatal tonsils hypertrophy	Palatal tonsils grading	+ to ++	+	Red
	Lingual tonsils hypertrophy	Lingual tonsils grading	+ to ++	+	Red
Tongue (Consider DISE and/or MDCT as first-line assessment tools)	Macroglossia	Tongue reduction surgery	++	+	Yellow
Pharyngeal airway (Consider DISE as first-line assessment tool)	Obstruction level	Main obstruction level	++ to +++	+	Yellow
	Obstruction severity	Main obstruction severity	++	+	Yellow
	Obstruction type	Main obstruction type	++	+	Red
Hyoid bone (Consider MDCT as first-line assessment tools)	Hyoid bone morphology	Hyoid bone suspension surgery	++	+ to ++	Green
Mandible (Consider MDCT as first-line assessment tools)	Genial tubercle position	Genioglossus advancement surgery	+ to ++	++	Green
Airway-based treatment (Consider DISE and/or MDCT as first-line assessment tools)	Hard tissue segmentation for surgical planning	MMA surgery	+++	++	Green
	Treatment outcomes prediction	Eligibility for MAD	+++	+	Yellow
	Treatment outcomes assessment	RME effects on tongue position	++ to +++	+	Yellow
SDB (Consider PSG and/or DISE as first-line assessment tools)	OSA diagnosis	AHI prediction based on airway obstruction	+++	+	Red
	OSA anatomical risk factors	Screening for OSA risk	+++	+	Yellow

+ = small/low; ++ = medium; +++ = large/high.
Green = good scientific support; yellow = questionable scientific support; red = little scientific support.
Abbreviations: AHI = apnoea hypopnoea index, DOME = distraction osteogenesis maxillary expansion, FOV = field of view, NE = nasal endoscopy, DISE = drug-induced sleep endoscopy, PSG = polysomnography, MDCT = multi-detector CT, MAD = mandibular advancement device, MMA = maxillomandibular advancement, OSA = obstructive sleep apnoea, RME = rapid maxillary expansion, SDB = sleep-disordered breathing, TADs = temporary anchorage devices.
*Symbols only represent the most common setting that may be used for the reported application example, and every clinical situation must be assessed individually.

innovative applications, and potential future outlooks about the use of CBCT are discussed with a special focus on upper airway analysis in patients with SDB.

Indications for the use of CBCT in orthodontics

For most radiographic analyses in orthodontics, two-dimensional (2D) imaging is the gold standard, especially lateral cephalometric radiography (LCR)[19] and dental panoramic radiography (PR).[20] Nevertheless, X-rays should be used only if beneficial for diagnosis and influential for clinical decision-making.[21] CBCT reduces the image distortion that is present in LCR and PR[22] and overcomes limitations related to the overlapping of anatomical structures. CBCT also allows the measurement of airway volumes,[23] which is an advantage over LCR.[24] However, CBCT may not be indicated in all cases, and specific applications need to be discussed independently.

Anomalies of the dentition (small FOV)

Extraction of impacted third molars may be required before orthodontic treatment.[25] Although PR imaging is sufficient in most situations,[26] CBCT may be suggested when signs for a close contact between the tooth and the mandibular canal are present in the 2D image and it is believed that CBCT findings might alter the surgical approach.[27] Impacted canines also have implications on orthodontic treatment outcomes, and[28] although CBCT may not offer advantages compared to 2D imaging in all cases,[29] it provides more details on canine position and possible root resorption of adjacent incisors prior to surgery.[30] In addition, radiolucent areas surrounding impacted canines and eruption anomalies of other teeth may be related to cyst formation and localized CBCT assessment may be indicated for differential diagnosis.[31] If CBCT images with a large FOV have already been acquired for planning maxillofacial surgery, they may also be used for diagnosing dental agenesis[32] or supernumerary teeth.[33] Lastly, in the case of facial trauma with dento-alveolar or jaw fractures,[34] CBCT assessment can provide important information when tooth replantation, orthodontic splinting, or surgical extraction with orthodontic space closure is considered.[35]

Temporomandibular joint (small to medium FOV)

Cone-beam CT can be used to assess the temporomandibular joint (TMJ). Here, the FOV usually includes the condyle, glenoid fossa, and articular eminence, ideally with both TMJs imaged (either in the same FOV or separately) for anatomical comparison.[36] Well-documented applications of CBCT are reported for the assessment of TMJ osteoarthritis.[37] In addition, CBCT imaging of the TMJ can be a valid aid in the diagnosis of expansive lesions of the mandibular condyle,[38] condylar hyperplasia,[39] and condylar fractures.[34]

Craniofacial malformations (medium to large FOV)

Cone-beam CT with variable FOVs has been used in patients with cleft lip and palate,[40] as they may receive alveolar bone grafting[41] and multiple orthodontic treatments at different ages.[42] CBCT has good reliability in the volumetric measurement of the cleft defect,[43] and CBCT-based classifications are available for cleft diagnosis.[44] In addition, patients affected by Treacher Collins syndrome, Pierre Robin sequence, or severe OSA may undergo CBCT assessments with large FOV for surgical planning.[45] For these patients, 3D images can also be used to design osteosynthesis systems by using computer-aided design and computer-aided manufacturing technology.[46] Furthermore, patients with severe sagittal skeletal discrepancies[47] or facial asymmetries may undergo orthognathic surgery,[48] and CBCT images can be used to plan surgical segmentation of the bones and to simulate their movements. Even though stereophotogrammetry and light-scanning are the gold standard for clinical acquisition of facial soft tissue morphology,[49] CBCT imaging using a large FOV may be available and it can be used to measure soft tissue changes following orthognathic surgery.[50] Hence, research articles have developed 3D cephalometry[51] and have assessed growth-related changes of facial soft[52] and hard tissues.[53]

Orthodontic treatment planning and outcome assessment (large FOV)

Cone-beam CT scans with large FOVs can be combined with intra- and extra-oral scanning for high-resolution recording of the facial surface[54] and dental morphology,[55] while the superimposition of small FOV scans with MRI may improve the diagnostic accuracy of TMJ disorders.[56] Such computer-based superimpositions can be used for comprehensive multidisciplinary planning of complex cases.[57] Moreover, software combining CBCT volumes and digital models allow the simulation of dental movements in aligner therapy and virtual placement of orthodontic brackets.[58] However, considering the cost–benefit in terms of X-ray exposure among the above-mentioned procedures, the use of CBCT may be justified only for the virtual planning of the position of skeletal anchorage devices in critical anatomical areas.[59]

Skeletal growth (large FOV)

Skeletal growth assessment is relevant to identify the optimal timing for treatment of deficient mandibular growth,[60] or prior to perform non-surgical rapid maxillary expansion (RME).[61] Techniques to evaluate skeletal maturity include the X-ray of the hand-wrist,[62] and the cervical vertebral maturation (CVM) method by using a LCR.[63] Since CBCT imaging is not limited by the overlapping of anatomical structures, the analysis of the fusion of the spheno-occipital synchondrosis has become clearer, and has shown good association with CVM.[64] Similarly, the midpalatal suture can be visualized on CBCT scans, and assessment methods of its maturation have been proposed.[65] However, methods based on the spheno-occipital synchondrosis do not offer clinically meaningful advantages over current standards based on 2D X-rays, while techniques based on the midpalatal suture have limitations in the cross-sectional staging of individuals[66] and in predicting the outcome of RME.[67]

Future outlooks and developments

Analysis methods supported by artificial intelligence may further enhance the role of CBCT. For example, deep convolutional neural networks can be used for automated classification of anatomical structures[68] and pathological conditions may be identified thanks to machine learning based on big data.[69] Furthermore, with the progress of virtual reality (VR), the applications of CBCT in orthodontics may extend to fully digital workflows, with accurate simulations of treatment outcomes[70] Lastly, VR can facilitate the introduction of CBCT in undergraduate and postgraduate teaching,[71] especially for orthodontic training.[72] Throughout this process, however, data safety become more of a concern. In fact, CBCT information on patient dentition and facial structures may be used for facial recognition and patient identification.[73]

Upper airway analysis on CBCT scans

The upper respiratory tract begins with the oro-nasal cavities, proceeds with the pharynx, and terminates at the level of the larynx. Besides allowing the air to flow to the lower airway for gas exchange, the upper airway is constituted by organs and tissues that control moisture and temperature, and reduce the risk of infections.[74] The American Academy of Orthodontics has encouraged clinicians to screen patients for OSA, identify signs and symptoms, assess underlying dentofacial components, and assist physicians in managing the disease.[75] For example, RME may be effective in the management of paediatric OSA,[76] and it can be considered in cases of transverse maxillary deficit.[77] OSA is diagnosed based on cardiorespiratory and neurological parameters via polysomnography (PSG), while drug-induced sleep endoscopy (DISE) is the gold standard for identifying the characteristics of the upper airway obstruction,[78] which are important for optimal treatment planning based on individual features.[79] However, DISE requires sedation, cardiorespiratory monitoring, and trained personnel that may not be readily available in most settings.[80] CBCT has numerous applications in orthodontics and—when already available—images can be retrospectively analysed for extrapolating useful information on the upper airway morphology. Nevertheless, prospective clinical applications are questionable, and detailed understanding of advantages and limitations of CBCT imaging is necessary to judge its appropriateness for analysing specific anatomical features of the upper airway.[10]

Nasal cavity

The nasal cavity assessment focuses on the anatomy and anomalies of the nasal septum, nasal turbinates, and nasal floor. Small-to-medium FOV CBCT scans can be used for this purpose, with a volume extending from the nasal floor to the top of the nasal septum.

Nasal septum

Septal deviation may increase the nasal resistance to airflow, which may create unfavourable pressure gradients that negatively affect air intake and may predispose to upper airway obstruction.[81,82] The assessment of the nasal septum can be done via CBCT, and specific grading methods have been proposed.[83] Such evaluation is particularly relevant in the presence of nasal obstruction leading to mouth breathing and SDB.[84] Patients with this condition may benefit from RME, as it potentially enlarges the nasal cavities[85] and may even reduce septum deviation.[86]

Nasal turbinates

Nasal turbinates may be subject to mucosal hypertrophy.[82] Swollen turbinates due to allergy or infections can impair nasal breathing and contribute to SDB.[87] Their inspection is usually performed via anterior rhinoscopy or nasal endoscopy. These procedures allow clear assessment of tissue hypertrophy with respect to the lumen of the nasal airway, and to appreciate the inflammatory status of the mucosa.[88] CBCT imaging may be indicated in cases of concomitant sinus pathologies or concerning masses,[89] and when nasal endoscopy is contraindicated, unavailable, or when the patient is uncooperative.[90] CBCT can be used to measure the hypertrophy of nasal turbinates,[91] and specific methods have been developed for turbinates grading in patients with cleft lip and palate.[92] Since turbinate hypertrophy is often a compensatory reaction to protect the nasal passage from cold and dry air in the presence of nasal septum abnormalities,[91] orthodontic intervention with RME may be beneficial.

Nasal floor and nasal valve

The narrowest portion of the nasal cavity is the internal nasal valve, which constitutes the point of maximum airflow resistance.[93] During inspiration, the airflow increases in the fixed nasal volume, leading to a pressure decrease. Hence, if the flow rate is disproportionate, the upper lateral cartilage collapses and acts like a valve protecting the airway.[94] When the internal nasal valve and nasal floor are excessively narrow, treatments such as surgical RME—which involves a distractor fixed onto the palate via orthodontic mini-screws—can significantly reduce the nasal obstruction.[95] CBCT imaging, in addition to nasal cavity assessment, allows for the visualization of the thickness of the nasal floor for optimal selection and positioning of mini-screws.[96]

Tonsils

Pharyngeal, lingual, and palatal tonsils are constituted by lymphoid tissue, with low density and radiopacity.[97] Nevertheless, the high contrast with respect to the airway makes the tonsils clearly visible via CBCT, allowing for direct measurements of their size[98] and of the intramural airway space.[8] This said, limited evidence is available about the validity of CBCT imaging for tonsils assessments and its application as a screening tool for tonsillar hypertrophy is questionable.[99]

Pharyngeal tonsils

Also known as adenoids, pharyngeal tonsils are located in the nasopharynx. Their hypertrophy may lead to upper airway obstruction[100] and altered craniofacial development associated with mouth breathing.[101] Adenoid hypertrophy is among the most common causes of SDB in children, and adenotonsillectomy is often the first-line treatment of paediatric OSA.[102] The gold standard for the grading of adenoid hypertrophy is nasal endoscopy.[103] Still, the obstruction severity at the adenoid level can be estimated via LCR or CBCT by using similar scoring methods, which are based on the ratio between the tonsil size and the nasopharyngeal space.[104] CBCT has good reliability and validity in the diagnosis of adenoid hypertrophy, but the assessments performed by orthodontist may be suboptimal[104] and reports supporting its validity in patients with SDB are scarce.[90] In addition, CBCT does not allow for the visualization of the mucosal status—including possible inflammation and infections—and the intramural soft tissue component. Thus, further MRI or endoscopy assessment may be indicated for accurate diagnosis.[105]

Lingual tonsils and palatine tonsils

Lingual and palatine tonsils can be hypertrophic and may contribute to SDB, albeit adenoids have greater relevance in upper airway obstruction. While palatine tonsil hypertrophy is present mainly in adults with OSA,[106] swollen lingual tonsils are more relevant among children.[107] Isolated reports of palatine[90] and lingual tonsil[98] assessment via CBCT are available, but there is no indication for routine clinical use. Compared to the adenoids, which are supported by the sphenoid bone, lingual tonsils are attached to the tongue, which makes them mobile and subject to motion artefacts. While the assessment of palatine and lingual tonsils is limited by the poor contrast resolution of CBCT for soft tissue, the use of hard tissue landmarks may overestimate their volume.[98]

Tongue

Although the tongue is a mobile structure, its position and volume have been assessed via CBCT in patients with OSA, for the selection of those that may benefit from surgery of the retroglossal area.[108] Tongue surgery often aims at reducing excessive tongue volume in the presence of macroglossia due to genetic conditions, such as Beckwith–Wiedemann syndrome associated with OSA.[109] The tongue posture is affected by gravity, and most CBCT scanners are designed to accommodate the patient either standing or seated. However, CBCT imaging is also possible with the patient in a prone, supine, or lateral recumbent posture.[110] Notably, OSA may have a positional component,[111] and standing during CBCT acquisition may affect the soft tissue morphology of the upper airway compared to the sleeping posture.[112] Thus, patients with SDB and indications for CBCT imaging may benefit from scanners designed for image acquisition of patients lying horizontally. Because of the susceptibility of tongue collapse in supine position, mandibular advancement devices (MAD) have been developed to target this anatomical structure.[113]

Pharyngeal airway

Compared to the non-collapsible nasal cavity, the pharyngeal airway—which is divided in nasopharynx, oropharynx, and laryngopharynx—is a collapsible structure. Assessment of upper airway obstruction in patients with SDB is mainly performed via DISE, as SDB manifests during sleep. However, CBCT scans are taken while the patient is awake, and obstructive events may not be visible. Furthermore, the static assessment offered by CBCT does not allow for the appreciation of the dynamic motion of the upper airway.[114] This aspect may compromise the application of standard scoring methods used in DISE, in which categories are based on the dilation and obstruction of the upper airway during breathing. Therefore, the validity of CBCT with respect to DISE has intrinsic limitations and remains of controversial reliability.[8] Still, CBCT with a large FOV may be used in patients with severe OSA, such as adults undergoing surgical maxillomandibular advancement (MMA) or children with craniofacial syndromes requiring orthognathic surgery.[115] Thus, reports of upper airway assessment via CBCT are available in the published literature,[116] including image reconstructions that simulate 3D virtual endoscopy,[114] and the assessment of obstruction characteristics via CBCT imaging is worth critical discussion.

Obstruction severity

Obstruction severity may range from no obstruction, to partial obstruction, to complete obstruction. Using CBCT for cross-sectional assessment of obstruction severity (ie, evaluating the patient by using images acquired at a single timepoint) has methodological constraints as CBCT imaging cannot be taken selectively when the maximum obstruction is present, and it is not valid for assessing its severity. Even though the upper airway of subjects with OSA might be, on average, narrower than in healthy individuals,[117] CBCT imaging may still have limitations in the identification of the presence/absence of obstruction. In fact, currently proposed CBCT-based norms of upper airway size are subject to great individual variability, with SD accounting for about half of the reference values.[118] Additional factors such as age[119] and ethnicity[120] further compromise the clinical application of such norms to assess the presence of obstruction. Thus, they may not allow for the establishment of meaningful cut-off values to discriminate between pathological and physiological conditions, although the use of ratio to adjust for different head sizes and ethnic-specific norms may reduce this limitation. Nevertheless, acceptable sensitivity cannot be excluded in case of findings showing a completely obstructed upper airway. On the other hand, longitudinal assessments (ie, comparing the images of the same patient at two different timepoints) are not affected by individual variability, and may provide useful information for the analysis of treatment outcomes, such as changes of upper airway patency following MMA in adults[116] or RME in children.[85]

Obstruction level

Obstruction is conventionally assessed at different levels of the upper airway (eg, nasal, adenoids, velum, lateral pharyngeal walls, retroglossal, and supraglottis), and—in some cases—multiple levels may be simultaneously obstructed.[121] Each level may have specific susceptibility to the previously described CBCT limitations. For example, one study showed association between the presence of obstruction on DISE and CBCT at the oropharynx, but no association between the two methods at the tongue or epiglottis level.[122] Other authors focused on the reliability of CBCT in measuring upper airway volumes, showing excellent consistency at the oropharynx but lower consistency at the nasopharynx and hypopharynx.[8] Such differences may be attributable to the presence of structures with complex anatomy (eg, the epiglottis), to the variable extent of soft tissue collapsibility during breathing (eg, soft palate vs. adenoids), and to the effect of head posture (eg, gravity on tongue position).[123] Thus, CBCT may not be a valid alternative tool to DISE when the identification of the obstruction level is necessary for optimal treatment planning[124] such as for the application of MAD in cases of retroglossal collapse.[125]

Obstruction type

The pattern of upper airway obstruction can be further classified as antero-posterior (ie, ventro-dorsal linear pattern), latero-lateral (ie, transverse linear pattern), or concentric (ie, circular pattern), according to the movement of the pharyngeal soft tissues. This assessment requires the appreciation of the motion type of the soft tissues during their dynamic collapse (ie, the changes of the airway lumen over time during breathing). Such information may affect orthodontic treatment planning, as the OSA severity in patients with by concentric collapse (at the soft palate) and latero-lateral collapse (at the oropharynx) may even worsen under MAD therapy.[125]

Other structures relevant for upper airway

When CBCT scans with large FOVs are available, they can be used to identify the position of the hyoid bone,[126] which is of specific interest for patients with OSA.[127] In fact, the hyoid bone supports the insertion of the mylohyoid muscle, which contributes to the mandibular position and affects tongue posture.[128] Notably, surgical suspension of the hyoid bone is a treatment option for OSA.[128] In addition, genioglossus advancement may be considered,[129] as the genioglossus muscle connects the tongue to the genial tubercle of the mandible, which can be localized with CBCT imaging for surgical planning.[130] Overall, from a practical perspective, multiple anatomical structures may be relevant during upper airway assessment and not all CBCT units can provide the appropriate FOV size. Therefore, specialized infrastructure with sufficiently large CBCT scanners and trained personnel may be necessary for optimal image acquisition.

Airway-based treatment

Although CBCT imaging is neither recommended for standard orthodontic procedures,[18] nor constitutes an alternative tool to conventional imaging used for upper airway assessment,[131] large FOV volumes may be indicated for selected patients.[115] Thus, CBCT may be a useful aid for clinical and research purposes once its limitations are clearly understood and if appropriate analysis methods are used.[10] Despite its limitations with respect to endoscopy, CBCT allows precise quantitative measurements of distances, angles, cross-sectional areas, surface areas, volumes, and shapes.[132] Thanks to these features, manual or automatic segmentation allows for the isolation of tissues with different contrast, including hollow cavities such as the upper airway.[133] Furthermore, superimposition with other imaging tools such as MRI can provide comprehensive assessment of both soft and hard tissues,[9,134] and computer software can be used to pre-visualize surgical procedures affecting the upper airway volume.[9] Similarly, post-treatment comparisons can be produced for better understanding of the effects on the upper airway of orthodontic therapies such as MAD, RME, and fixed appliances.[11] Lastly, limited to research applications, finite element analysis (FEA) can be paired with computational fluid dynamics (CFD) to simulate the airflow in the upper airway of a patient.[113] This said, segmentation, superimposition, and computations are possible when the clinical settings of CBCTs—that are indication-oriented and patient-specific—satisfy the research requirements—that are hypothesis-oriented and aim-specific.

Diagnosis of sleep-disordered breathing

Upper airway obstruction and SDB are conceptually different. SDB is a condition related to altered air flow that cannot be evaluated via CBCT imaging. Proper diagnosis of SDB—which includes OSA as the most severe condition—is complex and requires monitoring of pulmonary, neurological, and cardiovascular parameters via PSG.[12] Nevertheless, some studies have shown association between OSA and narrow upper airway measured on CBCT, proposing cut-off values to predict the severity of the disease in children with OSA based on the volume of the upper airway.[135] Another MRI study has suggested a cut-off value for identifying adults at greater risk of OSA,[136] presenting the possibility to develop OSA screening methods via CBCT as well.

Limitations of CBCT imaging in upper airway assessment and SDB diagnosis

In summary, CBCT has the following limitations:

- It offers a one-time picture of a dynamic process, namely the movement—and possible collapse—of the soft tissue constituting the upper airway. This limitation might be overcome by the use of modified 4D CBCT protocols, which involve very high radiation doses and their experimental application is currently limited to other body parts.
- The standing or seated pose differs from the sleeping posture, and the effect of gravity may result in soft tissue movements that are not representative of the actual obstruction. Thus, CBCT scanners that accommodate patients in a horizontal position may be preferred.
- Cardiorespiratory and neurologic parameters that are necessary for accurate diagnosis of SDB cannot be measured via CBCT, which is an intrinsic limitation of this imaging method.
- Images are acquired by using ionizing radiation, which is a further intrinsic limitation of CBCT. Acquisition parameters can be adjusted to minimize the effective radiation dose, but possible reduction in diagnostic accuracy should be considered.
- Mucosal status and intramural soft tissue component cannot be assessed. However, soft tissue swelling can be used as indirect indication of inflammation/infection.

On the other hand, CBCT:

- Allows quantitative measurements of distances, areas, and volumes, which are particularly important for upper airway assessment in both clinical and research settings.
- Has indications—to be considered in accordance with the ALADAIP principle—for dentoskeletal diagnosis and surgical planning, which is relevant for patients with OSA affected by craniofacial malformations.
- Can be combined with other imaging methods, such as MRI and optical dental scanning, for comprehensive assessment of TMJ disorders and occlusion before the fabrication of MAD.
- Allows for the assessment of underlying dentofacial structures that can be useful in the screening of patients at risk of SDB and for the planning of the orthodontic treatment.

Conclusions and future outlook in clinical practice and research

The following general recommendations on the use of CBCT in orthodontics can be made:

- CBCT has specific clinical applications for the diagnosis of dental anomalies, TMJ disorders, and craniofacial malformations. However, CBCT should not be routinely used for orthodontic diagnosis or treatment planning, and the use of large FOV should be limited to complex cases of craniofacial malformations.
- Guidelines are available for good clinical practice in the use of CBCT imaging for dentoskeletal abnormalities of orthodontic relevance, but more detailed clinical recommendations could be developed.
- Orthodontists should be familiar and updated regarding the multiple set-up options that CBCT imaging offers, for optimizing the appropriateness of their requests for 3D imaging.

The following critical observations on the use of CBCT for upper airway assessment can be made:

- CBCT imaging cannot be used to diagnose SDB, but may be used to visualize upper airway anatomy. Thus, CBCT imaging may contribute to orthodontic treatment planning based on upper airway analysis. To maximize the usefulness of CBCT imaging, orthodontists should have good knowledge of upper airway abnormalities in the context of SDB.
- Guidelines and recommendations should be developed to provide clear indications about the appropriate use of CBCT for upper airway assessment, including a list of which specific clinical questions may justify its prescription and which may not.
- Although taking CBCT scans solely for SDB screening is not recommended, patients with CBCT findings of anatomical risk factors associated with symptoms indicating SDB should be considered at risk and might benefit from

further assessment by a sleep specialist. Early screening for SDB via non-invasive radiation-free methods is advised so that optimized scanning modalities can be chosen if CBCT imaging is planned at a later time.

Future research on the use of CBCT in orthodontics is needed:

- To develop distinct and user-friendly CBCT acquisition protocols for each macro-area of orthodontic diagnostic question, aiming at further reducing radiation exposure in young individuals.
- To critically analyse the validity of CBCT compared to nasoendoscopy for upper airway assessment, with special focus on obstruction severity and localization, including patient samples with SDB, and accounting for the most relevant aspects that characterize upper airway obstruction.

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Conflicts of interest

All authors declare to have no conflict of interest with regard to this manuscript.

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