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REVIEW

Novel low-dose protocols using cone beam computed tomography in dental medicine: a review focusing on indications, limitations, and future possibilities

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Abstract

Objectives A narrative review on the potential use of low-dose protocols for cone beam computed tomography (CBCT) was conducted to identify indications and their relevance for various dental disciplines.

Materials and methods Google Scholar was searched using the words "low-dose CBCT". Reviews, consensus papers, clinical studies, and experimental studies were eligible for the initial screening process, but for data extraction only original articles were selected. Similar search procedures were then performed with the additional search words "pedo," "ortho," "endo," "implant," "perio," and "oral surgery." Furthermore, references of included articles were examined to identify further relevant articles.

Results After screening, 27 publications remained for the data extraction process. Low-dose protocols have been reported for specialties such as pediatric dentistry (evaluating orofacial clefts, periapical lesions, impacted teeth, and autotransplantation), orthodontics (cephalometric analysis and interim assessment of treatment results), endodontics (detecting root fractures, resorptions and periapical bone loss), implant dentistry (planning implant insertion, evaluating peri-implant fenestration and dehiscence), periodontology (assessing periodontal structures), and oral and maxillofacial surgery (assessing mandibular third molars and TMJs). Nevertheless, most of the literature available is related to non-clinical studies. Furthermore, there is a lack of position statements or guidelines from authoritative bodies regarding the use of low-dose protocols in dental medicine.

Conclusions Low-dose protocols for CBCT imaging seem to have potential in various disciplines in dental medicine ranging from pediatric dentistry to oral and maxillofacial surgery. Dose reduction is usually achieved by mAs reduction, use of partial rotations, reduced number of projections, and larger voxel sizes, but seldom by kV reduction.

Clinical relevance Albeit low-dose protocols have potential to result in a reduction of dose exposure for 3D imaging due to dental indications, there is a need to more clearly specify indications and limitations to avoid indiscriminate use of standard and high-dose CBCT scans in the future on the lines of ALARA/ALADA principles.

Keywords CBCT · Low-dose protocol · Indications · Limitations · ALARA · ALADA

Introduction

The initial description and introduction of cone beam computed tomography (CBCT) for use in dental medicine took place over two decades ago by an Italian group from Verona [1]. Since then, CBCT has had a great impact in diagnostic imaging and treatment planning in various dental specialties ranging from oral surgery to orthodontics. CBCT machines and their accompanying software have provided a relatively fast and convenient way to acquire and output three-dimensional (3D) multiplanar images, for which the scans can be taken in a supine, standing or seated position [2, 3]. CBCT imaging has become widely available and easily accessible to a large number of users in universities, dental hospitals, and also in dental practice. Nevertheless, CBCT scans have a significantly

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higher radiation dose than other conventional two-dimensional (2D) imaging modalities in dental medicine (e.g., intra-oral, panoramic, and cephalometric radiography). Therefore, various authoritative bodies have issued position statements or guidelines that detail the use of CBCT for specific circumstances in numerous dental disciplines, with some of the examples listed below:

- The European Academy of Dental and Maxillofacial Radiology (EADMFR) [4] and the Swiss Association of Dentomaxillofacial Radiology (SADMFR) [5, 6] regarding the use of CBCT in general.
- The SEDENTEXCT project which produced the European Commission guidelines that served as a basis for national guidelines worldwide [7];
- The "Dentomaxillofacial paediatric imaging: an investigation towards low-dose radiation induced risks" (DIMITRA) group regarding paediatric dentistry [8];
- The American Academy of Oral and Maxillofacial Radiology (AAOMR) regarding orthodontics [9];
- The European Society of Endodontology (ESE) and the AAOMR/American Association of Endodontists (AAE) regarding endodontology [10, 11];
- The American Academy of Periodontology (AAP) regarding periodontology [12];
- The European Association for Osseointegration (EAO), the International Congress of Oral Implantologists (ICOI) and the International Team for Implantology (ITI) regarding implant dentistry [13–15]

The 3D visualization of oral and maxillofacial structures by CBCT images provides information for diagnosis, treatment planning, and follow-up. For example for pediatric dentistry, CBCT scans help in evaluating orofacial clefts and in planning autotransplantation procedures [8]. For orthodontics, it is recommended to consider taking CBCT scans to plan orthognathic surgeries and correct jaw asymmetry [9]. For endodontology, a CBCT scan using a limited field-of-view (FOV) is considered an adjunctive imaging modality to diagnose periapical pathology, where periapical radiographs are not conclusive, examine extended dento-alveolar trauma, and assess complex root canal anatomy/calcified canals before commencing endodontic treatment or to plan periradicular surgery [10, 11]. For periodontology, the available literature is limited, but an accepted indication is the assessment of furcation defects to support the selection of an adequate treatment modality [12]. For implant dentistry, CBCT helps in implant treatment planning by evaluating bone dimensions and to assess the need for augmentative procedures (simultaneous or staged), and the health or pathology of the maxillary sinus [13, 14].

With regard to the versatility and increasing popularity of CBCT imaging in dental medicine, evidence is pointing towards indication-oriented and patient-specific imaging [8], and highlights the concept of dose optimization [16], which will be discussed initially in the present review. Then, special emphasis will be given to review the use of novel low-dose protocols with CBCT imaging, and to provide clinical recommendations on the basis of the literature identified and presented.

Radiation dose exposure and aspects of dose protection

Radiation doses are reported to be relatively low for conventional 2D imaging in dentistry, whether they stem from intra- or extraoral methods [17]. Through the increasing popularity of 3D imaging with CBCT exposing patients to higher doses than 2D imaging, radiation dose protection has become more and more relevant and a focus of attention in dental medicine in recent years [5, 6]. One fundamental aspect to radiation dose protection is the implementation of the "as low as reasonably achievable (ALARA)" principle, coined by the International Commission on Radiological Protection (ICRP) in 1977 [18]. In 2014, the National Council on Radiation Protection and Measurements (NCRP) has proposed a shift from ALARA to ALADA ("as low as diagnostically acceptable"), to emphasize the importance of dose optimization in medical diagnostic imaging [16]. Such a shift is also advocated for dental CBCT, as CBCT is recommended as a supplementary imaging technique where conventional 2D dental radiography fails to provide enough diagnostic information, instead of being a tool that simply provides "pretty pictures" [16].

Each CBCT machine has different and device-specific FOVs, which can be roughly divided into large, medium, and small [13, 19]. Ideally, the FOV should be fully adjustable, meaning that the FOV is totally patient-specific and indication-oriented to fulfill the principle of optimization [8]. However, such technology is yet to be commercially available. A large FOV (e.g., diameter × height usually larger than 10 × 10 cm) captures the maxillofacial structures beyond the oral cavity and maxillary sinus floor. Meanwhile, a medium FOV (e.g., between 8 × 5 and 10 × 10 cm) captures dentoalveolar regions including one entire or even both jaws. Finally, a small FOV (e.g., below 8 × 5 cm) captures a localized area of several adjacent teeth with their periapical region [15, 19]. To test the exact effective radiation dose (Sv) of CBCT machines with different devices and imaging protocols, phantom heads have been used to simulate average adult males [19]. Results have shown a wide range of effective doses stemming from CBCT scans: 52–1410 μSv for a large FOV, 18–674 μSv for a medium FOV, 11–252 μSv for a small FOV, and 7–769 μSv for child protocols [15]. When comparing these values to effective doses reported for 2D extra-oral radiography in dentistry, the minimal value for a CBCT (11 μSv) is comparable to 0.2–2.0 times of a dental panoramic view, or 1.0–5.5 times of a cephalometric image [15]. Meanwhile, the range of effective doses for CBCT is usually lower than that of spiral CT in the context of orofacial imaging [20, 21].

Compared to medical radiology, this minimal value of 11 μSv is similar to the average effective dose from a knee radiograph, while the maximal value (1410 μSv) is comparable to a thoracic spine projection including an AP and lateral view [17]. Nevertheless, the maximal value for CBCT scanning is still below the average effective dose for a head CT (2000 μSv) or head angiography (5000 μSv) [17], though certain examinations such as a sinus CT can have a lower effective dose of 200 μSv [22]. Because of this variability in effective doses for a single imaging modality, the basic principles of radiation protection are of paramount importance. Thus, special consideration to justification and dose optimization for each CBCT taken should be given.

Justification is based on the principle that the use of radiation is expected to result in more benefits than harm to the patient [13]. Alternative modalities that involve less or even no radiation exposure (e.g., ultrasonography or magnetic resonance imaging) should also be considered whenever deemed appropriate. Meanwhile, dose optimization can be observed by confirming with the prescribing dentist regarding the FOV and resolution selection whenever in doubt, and monitoring or adapting scanning parameters chosen according to the patient exposed to radiation (for example, child versus adult). In addition, the use of thyroid shielding around the front neck could reduce the effective dose received by the thyroid gland and esophagus to one-third regardless of large, medium, or small FOVs [23].

Certain groups are at a higher risk upon radiation exposure, such as children and the embryo or fetus of pregnant women. Children have a larger lifetime attributable cancer mortality risk per dose unit [24]. Moreover, a recent article has estimated the lifetime attributable risk of radiation-induced cancer due to dental exposures for boys and girls, and concluded that girls generally have a higher risk than boys [25]. Meanwhile, there is always a concern about the radiation risk to the embryo or fetus of pregnant women, with the potential effects being prenatal death, intrauterine growth restriction, reduced head size, mental retardation, organ malformation and cancer [26]. However, consensus is lacking on the issue of radiation protection [27], and thus it is still very important to consider dose reduction whenever applicable. A prospective study using pediatric phantoms has reported that large FOVs would lead to a significantly higher dose for the brain and thyroid [28]. Therefore, one future direction could be the implementation of adaptable FOV for which the size and position are optimized according to the indication and patient [8].

Low-dose protocols can be defined as procedures that lower exposure factors without an unacceptable loss of image quality for diagnostic purposes [29]. Low-dose protocols have also been introduced for dento-maxillofacial imaging using CT scanning [30]. Nevertheless, as CBCT is more easily available and accepted for dental purposes and private practitioners, the present review will focus on CBCT only. After determining an optimized FOV for a particular patient, a CBCT scan can be acquired with even further lower radiation doses, by either using dose reduction settings pre-set by the manufacturers or adjusting imaging parameters for which the CBCT machine allows manually. Generally, so-called low-dose protocols may be achieved by reducing the tube current (mA), scan time (s), resolution (i.e., increasing voxel size), the number of projections, and/or adopting a partial rotation mode (e.g., 180° instead of 360° rotation) [13].

In recent years, several CBCT manufacturers have incorporated features into their machines to accommodate and facilitate image acquisition by low-dose protocols which allow easier dose optimization [31]. For instance, the newer

Table 1 Use of CBCT low-dose protocols for specific indications in pediatric dentistry

Publication	Type of publication	Indications	Low-dose protocol described	Justification
Oenning et al. [8]	Position statement	Evaluating orofacial clefts	Smaller FOV, partial rotation, mAs reduction	↓ Radiation does not affect the cleft assessment
		Evaluating inflammatory periapical lesions and dentigerous cysts	Lower resolution (voxel sizes)	↓ Resolution creates noise that does not reduce diagnostic image value
		Post-operative monitoring of autotransplantation	Smaller FOV, lower resolution, mAs reduction	↓ Dose does not affect the outcome
EzEldeen et al. [37]	Experiment with phantom	Pre-operative monitoring of autotransplantation	ProMax 3D Max (Planmeca Oy, Helsinki, Finland): ULD mode, FOV = 10×9 cm^2, voxel size = 0.15 mm, rotation = 210°	Better balance between image quality and radiation dose
		Post-operative monitoring of autotransplantation	ProMax 3D Max (Planmeca Oy, Helsinki, Finland): ULD mode, FOV = 5×5.5 cm^2, voxel size = 0.20 mm, rotation = 210°	Better balance between image quality and radiation dose
Hidalgo Rivas et al. [29]	Experiment with phantom	Evaluating impacted maxillary canines	3D Accuitomo F170 (J. Morita Mfg. Corp., Kyoto, Japan): 80 kV and 3 mA (down from 90 kV and 4–6 mA), FOV = 4×4 cm^2, voxel size = 0.08 mm, rotation = 360°	↓ Dose by 50% does not significantly reduce image quality

Table 2 Use of CBCT low dose protocol for specific indications in orthodontics

Publication	Type of publication	Indications	Low dose protocol used	Justification
Brown et al. [38]	Experiment with dry human skulls	Performing 3D cephalometric analysis	i-CAT Classic (Imaging Sciences International, Hatfield, PA, USA): FOV = 17 × 13.2 cm^2, voxel size = 0.04 mm, rotation = 360°, exposure time = 10 s (down from 40 s)	↓ Exposure time (s) and ↓ number of projections does not reduce dimensional accuracy
Cook et al. [39]	Experiment with human cadavers	Evaluating dimensions of buccal cortical bone plate	i-CAT 17-19 machine (Imaging Sciences International, Hatfield, PA, USA): 120 kV and 5 mA, exposure time = 4.8 s (down from 26.9 s), voxel size = 0.3 mm, rotation = 180° (down from 360°)	↓ Exposure time (*s*) and ↓ number of projections does not reduce linear measurement accuracy
Kusnoto et al. [40]	Experiment with clinical CBCT data set manipulated with reconstruction settings	Identifying cephalometric landmarks	i-CAT Next Generation machine (Imaging Sciences International, Hatfield, PA, USA): 120 kV, 5 mA, FOV = 16 × 13 cm^2, voxel size = 0.3 mm, projection = 76 (25% of default)	↓ Number of projections does not reduce subjective diagnostic quality of the images
Ludlow and Walker [41]	Experiment with phantom	Evaluating root angulations during interim assessment of orthodontic treatment results	i-CAT FLX machine (Imaging Sciences International, Hatfield, PA, USA): QuickScan+mode, 90 kV, 3 mA and 2 s (down from 120 kV, 5 mA and 3.7 s), FOV = 16 × 13 cm^2, voxel size = 0.3 mm, rotation = 180° (down from 360°)	↓ Dose has resulted in reduced image quality, which can be still acceptable for the mentioned indication

generations of ProMax 3D devices (Planmeca Oy, Helsinki, Finland) have an "ultra low-dose (ULD)" mode that optimizes and reduces the tube current and scan time. The CS 9300 machines (Carestream, New York, USA) have a "low-dose mode" button that serves the same function. Furthermore, Accuitomo and Veraview machines (J. Morita Mfg. Corp., Kyoto, Japan) allow users to choose a 180° instead of a 360° rotation, and to reduce the tube current (ranging from 2 to 10 mA). Through the reduction of FOV height and angle of rotation, the radiation dose including the dose to the eye lens can be significantly reduced [32]. Depending on the machine, it was reported that the doses for the same FOV could have up

Table 3 Use of CBCT low dose protocols for specific indications in endodontics

Publication	Type of publication	Indications	Low dose protocol described	Justification
Bechara et al. [42]	Experiment with extracted teeth	Detecting vertical root fractures	Accuitomo 3D machine (J. Morita Mfg. Corp., Kyoto, Japan): 76 kV, 6 mA, FOV = 6 × 6 cm^2, voxel size = 0.125 mm, rotation = 180° (down from 360°)	↓ Angle of rotation only lowers specificity but accuracy and sensitivity are not affected
Durack et al. [43]	Experiment with dry human skulls	Detecting external root resorption	3D Accuitomo 80 machine (J. Morita Mfg. Corp., Kyoto, Japan): 90 kV and 3 mA, FOV = 4 × 4 cm^2, exposure time = 9 s (down from 17.5 s), rotation = 180° (down from 360°)	↓ exposure time by using half-scan does not affect the outcome
Hashem et al. [44]	Experiment with fresh porcine skulls	Measuring endodontic linear parameters (e.g. pulp height)	Accuitomo machine (J. Morita Mfg. Corp., Kyoto, Japan): 60 kV and 2 mA, FOV = 4 × 4 cm^2, voxel size = 0.125 mm, rotation = 180° (down from 360°)	↓ Angle of rotation does not reduce measurement accuracy
Jones et al. [35]	Experiment with dry human skulls	Detecting horizontal root fractures	3D Accuitomo 80 machine (J. Morita Mfg. Corp., Kyoto, Japan): 90 kV, 2 mA (down from 5 mA), FOV = 4 × 4 cm^2, exposure time = 9 s (down from 17.5 s), rotation = 180° (down from 360°)	↓ mA and ↓ exposure time by ↓ angle of rotation does not affect the outcome
Lennon et al. [45]	Experiment with dry human skulls	Detecting periapical bone loss	Accuitomo 3D FPD machine (J. Morita Mfg. Corp., Kyoto, Japan): 90 kV, 4 mA, FOV = 4 × 4 cm^2, exposure time = 9 s (down from 17.5 s), rotation = 180° (down from 360°)	↓ Angle of rotation does not affect the outcome
Neves et al. [36]	Experiment with extracted teeth	Detecting external root resorption	Classic i-CAT machine (Imaging Sciences International, Hatfield, PA, USA): 120 kV, 8 mA, voxel size = 0.3 mm (instead of 0.25 mm)	↑ Voxel size does not reduce diagnostic value

Table 4 Use of CBCT low dose protocols for specific indications in implant dentistry

Publication	Type of publication	Indications	Low dose protocol described	Justification
Al-Ekrish [46]	Experiment with dry human skulls	Planning for implant insertion	Iluma machine (Imtek Imaging, Ardmore, OK, USA): 120 kV, 3.8 mA, exposure time = 7 s (down from 40 s), voxel size = 0.3 mm	↓ Exposure time does not reduce reliability or accuracy
Dawood et al. [47]	Retrospective study with clinical CBCT data	Planning for implant insertion	3D Accuitomo F170 machine (J. Morita Mfg. Corp., Kyoto, Japan): 2–3 mA (down from 5 to 6 mA), exposure time = 5.3 s (down from 17.5 s), FOV = 4 × 4 cm^2, rotation = 180° (down from 360°)	↓ mA, ↓ exposure time and ↓ angle of rotation does not reduce confidence of diagnostics
de-Azevedo-Vaz et al. [48]	Experiment with bovine bone blocks with implants	Detecting peri-implant fenestration- and dehiscence-type defects	i-CAT Next Generation machine (Imaging Sciences International, Hatfield, PA, USA): 120 kV, 5 mA, exposure time = 14.7 s (down from 26.9 s), voxel size = 0.2 mm (instead of 0.12 mm), FOV = 8 × 8 cm^2, rotation = 180° (down from 360°)	↓ Dose does not affect the detection of fenestration; a full-scan should be kept for the detection of dehiscence
El Sahili et al. [49]	Experiment with human cadavers	Planning for implant insertion	Carestream CS 9300 (Carestream Health Inc., Toronto, Canada) 2 mA (down from 6.3 mA), 78 kV, exposure time = 20 s (down from 40 to 60 s, voxel size = 0.09 mm	↓ mA, and ↓ exposure time do not affect linear measurements
Liljeholm et al. [50]	Experiment with dry human skulls	Planning for implant insertion	ProMax 3D Classic (Planmeca Oy, Helsinki, Finland) ULD mode, 90 kV, 5.6 mA (down from 8 mA), exposure time = 4 s (down from 12 s), voxel size = 0.2 mm, FOV = 8 × 8 cm^2, rotation = 200°	↓ Dose does not reduce visibility of the anatomical structures
Neves et al. [51]	Experiment with dry human skulls	Planning for implant insertion	i-CAT Next Generation machine (Imaging Sciences International, Hatfield, PA, USA) 120 kV, voxel size = 0.2 mm, rotation = 180° (down from 360°)	↓ Angle of rotation does not affect the diagnostics
Parsa et al. [52]	Experiment with human cadavers	Planning for implant insertion	NewTom 5G machine (NewTom, Verona, Italy): 110 kV, 0.57 mA, exposure time = 3.1 s (down from 4.8 s), FOV = 8 × 8 cm^2	↓ Exposure time does not affect the gray values at implant site
Sur et al. [53]	Experiment with human cadavers	Planning for implant insertion	3D Accuitomo (J. Morita Mfg. Corp., Kyoto, Japan): 80 kV, FOV = 6 × 6 cm^2, voxel size = 0.125 mm, 2 mA and full-scan/4 mA and half-scan (down from 8 mA and full-scan)	↓ mA does not affect the visibility of anatomical structures
Vasconcelos et al. [54]	Experiment with dry human skulls	Planning for implant insertion	Kodak 9000 machine (Carestream Health, Rochester, NY, USA) 60 kV, 6.3 mA (down from 15 mA), exposure time = 10.8 s, FOV = 7.5 × 3.7 cm^2, voxel size = 0.2 mm	↓ mA does not affect the linear measurements
Waltrick et al. [55]	Experiment with dry human skulls	Planning for implant insertion	i-CAT machine (Imaging Sciences International, Hatfield, PA, USA) 120 kV, FOV = 8 × 8 cm^2, voxel size = 0.4 mm (instead of 0.3 mm)	↑ Voxel size does not affect the linear measurements and visibility of the mandibular canal

to 15-fold difference between low-dose and high-resolution protocols [33]. Besides manual reduction of the tube current, tube current modulation is also very efficient in achieving a patient-specific dose optimization via body size estimation with initial scout images [34], which is implemented by VGI evo machines (NewTom, Verona, Italy).

As kV determines the image contrast by relating to the penetrating power of the x-ray beam generated from the CBCT machine, it is said that dose reduction through reducing mA can still retain the image quality [35]. Meanwhile, lowering the resolution (by increasing the voxel size) seems not to have a clear effect on the diagnostic value of CBCT images [36]. In other words, lowering the resolution for CBCT imaging may be an integral part of a low-dose protocols, while keeping the images "diagnostically acceptable" (ALADA). The utilization of low-dose protocols for specific aspects and specialties in dental medicine will be described in the next chapter.

Current use of low-dose protocols for CBCT in various disciplines of dental medicine

Since the current review has been designed as a narrative review using a standardized approach for gathering the relevant literature and not as a true systematic review, the following search strategy has been applied by the first author. First, Google Scholar was searched using the words "low-dose CBCT" (without quotations, thus not limiting to publications with the exact phrase). Reviews, consensus papers, clinical studies, and experimental (phantom and cadaver) studies were eligible for the initial screening process, but for data extraction only original papers were selected. Similar search procedures were then performed with the additional search words "pedo," "ortho," "endo," "implant," "perio," and "oral surgery." Furthermore, references of included articles were examined to identify further relevant articles. Lastly, the senior authors were consulted for additional references. As a result, approximately 700 publications were initially screened, 100 from the general search, and 100 each per specialty field. After screening, 27 publications remained (details provided in Tables 1, 2, 3, 4, and 5). Of these, 3 publications were related to pediatric dentistry, 4 to orthodontics, 6 to endodontics, 10 to implant dentistry, 1 to periodontology, and 3 to oral and maxillofacial surgery.

For pediatric patients, the Image Gently in Dentistry campaign supported the use of half-scan modes as a general rule for taking CBCT scans for pediatric patients [16]. Table 1 lists the use of low-dose protocols for specific indications in pediatric dentistry. The DIMITRA group has advocated the use of low-dose protocols specifically to evaluate orofacial clefts, inflammatory periapical lesions and dentigerous cysts [8]. Nevertheless, there has been no clinical study on low-dose protocols in pediatric dentistry. Meanwhile, Rivas et al. [29] have recommended reducing the kV and mA, to evaluate impacted maxillary canines. Besides, EzEldeen and co-workers have recommended the use of the ULD mode of the ProMax 3D machine for preoperative and postoperative evaluation of a planned autotransplantation [37].

For orthodontic patients, there is no position statement on the use of low-dose protocols (Table 2). However, Brown et al. [38] (based on experimental data from dry skulls) and Kusnoto et al. [40] (based on clinical CBCT data) recommended reducing the exposure time (and thus reducing the number of projections) when CBCT images are acquired for cephalometric analysis, though it should be noted that 2D, instead of 3D, cephalometric analysis is still the norm. Meanwhile, 3D cephalometrics was also done with images acquired from several CBCT devices using lower resolution and/or lower-dose scan modes [41].

For endodontic patients, there is no position statement or clinical evaluation on the use of low-dose protocols available (Table 3). Results from in vitro studies have shown that for detection of external root resorption, diagnostically acceptable dose reduction can be achieved by using a half-scan [43], and also by applying an increased voxel size [36]. Half-scans can also be used to detect periapical bone loss [45], root fractures [35, 42], and perform endodontic measurements [44].

For implant patients, there is currently no position statement or official guideline on the use of low-dose protocols for treatment planning or follow-up imaging procedures (Table 4). Dawood et al. [47] conducted a retrospective clinical study and concluded that reducing the mA and exposure time and the use of a half-scan can be used for implant planning without any loss in diagnostic value or efficacy for treatment planning purposes. These findings are largely confirmed by multiple studies using skulls or cadavers (Table 4). With regard to the detection of peri-implant bone loss, dose reduction to diagnose fenestration- and dehiscence-type defects can be achieved by using larger voxel sizes, and for fenestrations a half-scan is recommended [48].

Publication on low-dose protocols for periodontology and oral and maxillofacial surgery are still rare (Table 5). To assess periodontal structures, dose reduction can be achieved by reducing the kV and mA [56]. Similarly, mA and exposure time can be reduced for visualizing third molars [57, 58]. A half-

Table 5 Use of CBCT low-dose protocols for specific indications in periodontology and oral and maxillofacial surgery

Publication	Type of publication	Indications	Low dose protocol described	Justification
Al-Okshi et al. [56]	Experiment with phantom	Assessing periodontal structures	3D Accuitomo 170 machine (J. Morita Mfg. Corp., Kyoto, Japan): 80 kV (down from 90 kV), 5 mA (down from 9 mA), FOV = 8 × 8 cm^2, exposure time = 17.5 s, rotation = 360°	↓ Dose does not affect the visibility of the periodontal structures
de Melo et al. [57]	Experiment with dry human skulls	Assessing the mandibular third molars	Picasso Trio machine (Vatech, Hwaseong, South Korea): 80 kV, 3.5 mA, exposure time = 15 s (down from 24 s), FOV = 5 × 5 cm^2 (down from 12 × 8.5 cm^2), voxel size = 0.2 mm, rotation = 360°	↓ FOV and ↓ exposure time do not affect the outcome
Neves et al. [58]	Experiment with dry human skulls	Assessing the mandibular third molars	Kodak 9000 machine (Carestream Health, Rochester, NY, USA): 60 kV, 6.3 mA (down from 15 mA), exposure time = 10.8 s, FOV = 5 × 3.8 cm^2, voxel size = 0.2 mm	↓ mA does not affect the outcome
Yadav et al. [59]	Experiment with dry human skulls	Detecting degenerative changes of the temporomandibular joint (TMJ)	3D Accuitomo machine (J. Morita Mfg. Corp., Kyoto, Japan): 80 kV, 5 mA, FOV = 14 × 4 cm^2, exposure time = 9 s (down from 17.5 s), rotation = 180° (down from 360°)	↓ Angle of rotation does not affect the reliability

scan has been mentioned to be adequate for detecting degenerative changes of the temporomandibular joints (TMJ) [59].

It should be noted that the stated values for kV, mA and other exposure parameters depend on the individual CBCT machine used by the reported studies, and are not directly generalizable to all machines.

Clinical recommendations and conclusions

Most of the publications available supporting the use of low-dose protocols for various indications in dental medicine largely stem from benchmarking studies that involve cadavers, dry skulls, and phantom heads. As a result, most of the existing evidence may not have the highest level of methodological quality or clinical relevance. Notwithstanding, there is a consensus that the FOV size and location are major determinants of the effective dose, and thus the optimization of other imaging parameters should be done on the basis of FOV selection [31].

As the current evidence mainly came from non-clinical data, future research should primarily evaluate the possibilities and limitations of low-dose protocols using CBCT data from a clinical perspective. One future research direction is to produce multiple CBCT data sets, from a single patient scan, to simulate multiple scans of the same patient using different dose reduction settings. By doing so, the ethical issue of scanning a patient multiple times can be circumvented, while clinicians can evaluate the (simulated) effect of low-dose protocols on clinical data instead of data from phantoms or cadavers. This can be achieved by means of altering the reconstruction algorithm, which is similar to the method used by Kusnoto et al. [40]. Another direction is to retrospectively evaluate the diagnostic quality of existing CBCT data sets, such as proposed by Dawood et al. [47]. Moreover, the CBCT machines in the market have different options for users to change the imaging parameters. After basic confirmation of the efficacy or usefulness of low-dose protocols in practice, the applied studies should validate these results using and directly comparing various CBCT devices available on the market, so that users can directly apply these dose optimization protocols to their clinical practice. A recent review has concluded that there are 13 factors that relate to differences in the effective dose emitted by various CBCT scanners, listed as follows: (1) device-based—scan angle, additional copper filter, FOV diameter, FOV height, kV, mA, exposure time, mAs, voxel, and resolution; (2) non-device-based—patient size, region of interest, and use of thyroid shield [60]. As Jacobs et al. [20] have advocated, CBCT protocols should be both "patient-specific" and "indication-oriented," meaning that the FOV, resolution and radiation dose should depend on patient's age and anatomy and the diagnostic/therapeutic requirements.

Based on the present review of the available literature, the following statements can be made with regard to the use of low-dose protocols for CBCT in dental medicine:

- A low-dose protocol should be considered in various disciplines in dental medicine, specifically:

  – Pediatric dentistry (for indications such as evaluation of orofacial clefts, periapical lesions, impacted teeth, and prior to autotransplantation),
  – Orthodontics (cephalometric analysis and interim assessment of treatment results),
  – Endodontics (detecting root fractures, resorptions and periapical bone loss),
  – Implant dentistry (planning implant insertion, evaluating peri-implant bone loss), and
  – Oral and maxillofacial surgery (assessing mandibular third molars and TMJs).

- Dose reduction is usually achieved by mAs reduction, use of partial rotations, reduced number of projections, and larger voxel size, but seldom by kV reduction.
- Most of the publications on low-dose protocols using CBCT imaging are non-clinical studies.
- There is a lack of position statements, clinical recommendations, or guidelines from authoritative bodies regarding the use of low-dose protocol in dental medicine.

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Compliance with ethical standards

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