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Radiation dose in non-dental cone beam CT applications: a systematic review

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Abstract

Background Radiation-induced health risks are broadly questioned in the literature. As cone beam computed tomography (CBCT) is increasingly used in non-dental examinations, its effective dose needs to be known. This study aimed to review the published evidence on effective dose of non-dental CBCT for diagnostic use by focusing on dosimetry system used to estimate dose.

Materials and methods A systematic review of the literature was performed on 12 November 2017. All the literature up to this date was included. The PubMed and web of science databases were searched. Studies were screened for inclusion based on defined inclusion and exclusion criteria according to the preferred reporting items for systematic reviews.

Results Fifteen studies met the inclusion criteria and were included in our review. Thirteen and two of them examined one and two anatomical areas, respectively. The anatomical areas were: ear (6), paranasal sinuses (4), ankle (3), wrist (2), knee (1), and cervical spine (1). Effective dose was estimated by different methods: (i) RANDO phantom associated with thermoluminescent dosimeters (6), metal oxide semiconductor field-effect transistor dosimeters (3), and optically stimulated luminescent dosimeters (1). (ii) Scanner outputs, namely computed tomography dose index (1) and dose area product (2). (iii) Monte Carlo simulations (2).

Conclusion CBCT of extremities, cervical spine, ears and paranasal sinuses was found to be a low-dose volumetric imaging technique. Effective doses varied significantly because of different exposure settings of CBCT-units and different dosimetry systems used to estimate dose.

Keywords Radiation dosage · Effective dose · Cone beam computed tomography · Head and neck imaging · Skeletal imaging

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Introduction

Cone beam computed tomography (CBCT) is a volumetric imaging technique extensively used and well established in all areas of dental diagnostics [1–5]. Recently, it is increasingly used in the study of ears, paranasal sinuses, and extremities [6–8]. Numerous manufacturers today offer a wide range of CBCT-units with technical features which differ greatly [9]. There are horizontal and vertical units that examine patients in supine, seated, or upright positions. CBCT devoted to the study of ears and paranasal sinuses or designed to assess the extremities in weight-bearing position (i.e. under load) have newly entered the market as well [10].

The success of CBCT is mainly due to a relatively low radiation dose [11], limited metal artefacts [12], high spatial resolution (0.075–0.4 mm isotropic voxel) [13], and low maintenance and operating costs [14]. Nevertheless, CBCT is not used for contrast-enhanced examinations, does not have a high contrast resolution [15], and the scan time is long with non-negligible motion artefacts [16].

X-ray imaging for diagnostic purposes has gradually increased, which may have led to an increase in radiation-induced health risks [17–19]. For this reason, both in the USA (Senate Bill 1237) and Europe (Euratom directive 59/2013) legislations have been published that intensely request from operators to record the estimated patient dose of each radiation exposure in every radiology report [20, 21]. This may be useful not only for estimating the potential risk of radiation exposure but also for assessing protocol optimisation, standardisation, and quality assurance [22].

Currently, effective dose is the most commonly metric used to track patient dose and represents the stochastic health risk to the whole body, which is the probability to induce cancer and/or genetic damage from ionising radiation. It involves comparing dosimetric values from different examinations and modalities [23].

Radiation dose of CBCT in dental use was already discussed by different papers [24]. However, no review on the field of dosimetry of the latest non-dental CBCT applications has been carried out. Therefore, the purpose of this study was to investigate the existing literature concerning the effective dose of non-dental CBCT used for diagnostic aims. An additional purpose is to analyse the methods used to measure and estimate the effective dose.

Materials and methods

Literature searches

The literature review was carried out in conformity with the preferred reporting items for systematic reviews (PRISMA) statement for studies focused on the dosimetric evaluation of CBCT, except in dental applications. PRISMA is an evidence-based minimum set of items that helps authors to improve the reporting of systematic reviews, although it is not a quality assessment tool to estimate the merit of a research [25].

The search strategy was restricted to English-language papers via the PubMed and web of science databases. The following combined terms were investigated: radiation dosage, radiation protection, dose, effective dose, absorbed dose, and cone beam computed tomography (Table 1). For the aims of this review, these terms were defined as follows:

- Radiation dosage and radiation protection according to medical subject headings (MeSH).
- *Dose* a generic term including all kinds of doses described by the International Commission on Radiological Protection (ICRP) [26].
- *Effective dose* the sum of the products of the tissue weighting factors and the absorbed dose within the exposed tissues and organs of the body—established by the ICRP.
- *Absorbed dose* the quantity of ionising radiation absorbed by a body, measured as the energy absorbed per unit mass—established by the ICRP.
- *Cone beam computed tomography* a volumetric imaging technique with a conic/pyramidal X-ray beam of radiation.

The search in Pubmed included both MeSH and free-text terms, whereas the searches in Web of Science included only free-text terms. An additional manual search was performed using the reference lists of the examined studies. The searches were conducted on 12 November 2017.

Inclusion and exclusion criteria

We included studies published in international peer-reviewed journals that examined effective dose of non-dental CBCT for diagnostic use. Anatomical areas in the facial region which can have a relationship with tooth, such as temporomandibular joints, nose and sinonasal cavities were included. Original articles, case reports, short communications, letters to the editor, and conference proceedings were included.

Table 1 Search strategy

Indexing terms	Publications (*N*)
Pubmed	
#01 Radiation dosage [MeSH terms]	76,952
#02 Radiation dosage	128,749
#03 Radiation protection [MeSH terms]	19,449
#04 Radiation protection	36,398
#05 Dose	1,236,797
#06 Effective dose	144,960
#07 Absorbed dose	16,388
#08 Cone beam computed tomography [MeSH terms]	6520
#09 Cone beam computed tomography	9875
#10 = #01 OR #02 OR #03 OR #04 OR #05 OR #06 OR #07	1,281,659
#11 = #08 OR #09	9875
#12 = #10 AND #11	2136
Web of science	
Dose	1687
AND	
Cone beam computed tomography	
NOT	
Dental	

The exclusion criteria were:

- anything focusing on teeth;
- papers that did not focus on CBCT;
- papers that focused on CBCT for non-diagnostic purposes (e.g. guidance for radiotherapy);
- papers that did not relate to dose;
- papers in the field of dosimetry that did not estimate the effective dose.

Study selection and data extraction

Three reviewers independently examined the titles and abstracts of studies to determine their eligibility for inclusion. Screening the full text was done whenever the abstract did not give enough information to define eligibility. Moreover, the full text was read when at least one of the authors claimed that the study met the inclusion criteria. Data were individually extracted from each study on (1) the type of endpoint, (2) the anatomical area, (3) the physical and technical features of CBCT-units, especially scanning protocols, (4) the method to measure and estimate radiation dosage, (5) the features of dosimeters and phantoms, and (6) the effective dose.

In case of disagreement over the study selection or data extraction, the issue was solved by consensus discussion among the reviewers.

Results

Study selection

Fifteen studies met our inclusion criteria. Each stage of the search and screening processes with the number of papers identified, included, and excluded is shown in Fig. 1. The screening of the found articles, based on title and abstract reading, revealed 27 papers which were potentially eligible and consequently selected for full-text reading. After examination of the full texts, 12 papers did not meet the inclusion criteria. The main reasons for exclusion were that the studies did not focus on the field of dosimetry or did not report the effective dose. Among the 15 papers selected (14 original papers [27–40] and 1 conference proceeding [41]), two of them analysed two anatomical areas; all the others analysed only one anatomical area (Table 2). The following anatomical areas were analysed: ear [27–32], paranasal sinuses [27, 33, 34, 41], ankle [35–37], wrist [38, 39], knee [40], and cervical spine [32].

Features of CBCT-units

In the 15 studies examined, 16 CBCT-units (seven different models) were used, of which five were from the USA [29, 33, 34, 36, 41], Finland [31, 35, 37, 38, 40], and Italy [27, 28, 32, 35, 39], and the remaining one from Japan [30]. One study [31] used a modified specific acquisition system that involved a pause during each exposure of the multiple frames to reduce potential motion artefacts generated by the rotating "C" arm. No physical/technical parameter was referred to in the three studies [34, 37, 41]. The tube voltage was mentioned in all the other studies, whereas some of them did not report field of view (FOV) [28, 29], mAs [30, 38, 39], and voxel size [27, 28, 40].

Features of dosimetry systems for calculating effective dose

The studies analysed in the current review measured or estimated the effective dose by using the following methods (Table 3):

- *RANDO Phantom associated with three different kinds of dosimeters* thermoluminescent dosimeter (TLD) [27–29, 32, 33, 41], metal oxide semiconductor field-effect transistor (MOSFET) dosimeter [31, 35, 40], and optically stimulated luminescent dosimeter (OSLD) [36]. The features of dosimeters and phantoms were generally described in detail.

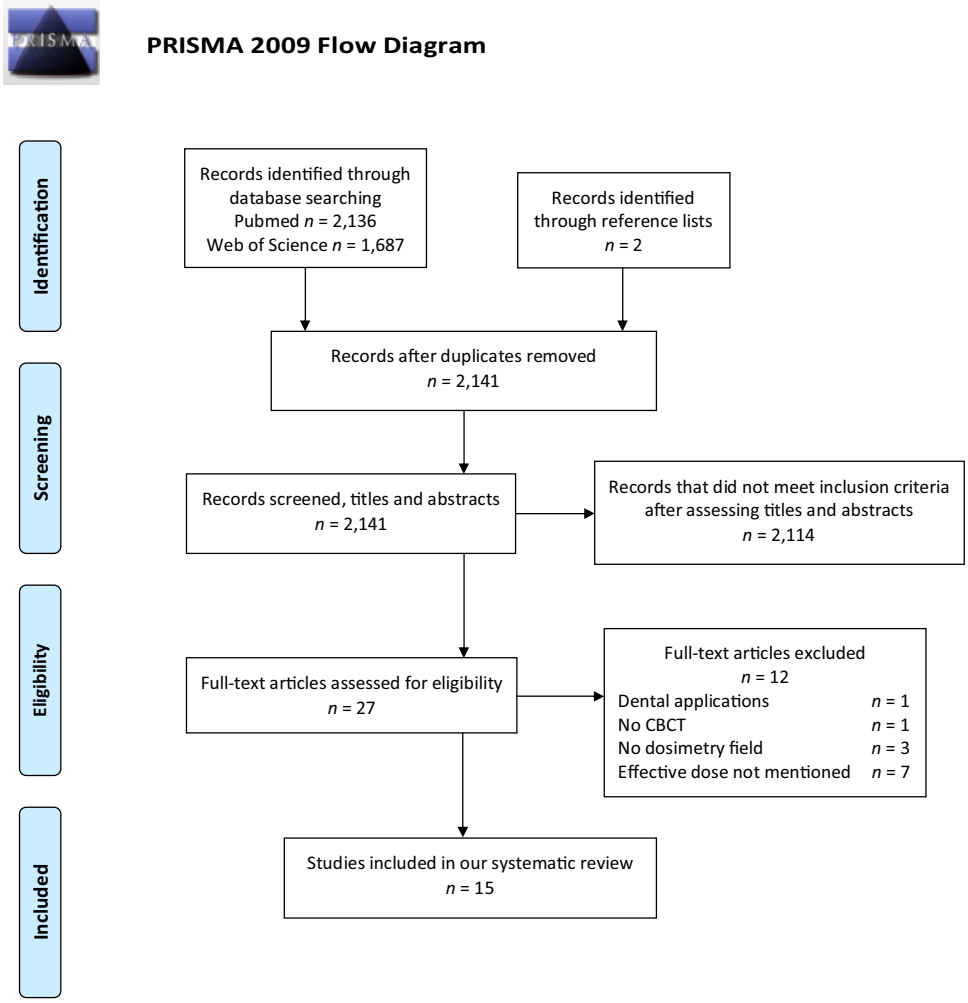

Fig. 1 Flowchart consistent with preferred reporting items for systematic reviews (PRISMA) statement

- *Scanner outputs* Computed tomography dose index (CTDI) [39] and dose area product (DAP) [37, 38], each of which was multiplied by a conversion factor.
- Monte Carlo simulations [27, 34].

One study [27] compared the effective dose calculated by Monte Carlo simulations and the effective dose measured by TLD, while another [30] did not even mention the method used to calculate the effective dose.

In addition, the dosimetric study was the primary endpoint in 10 studies [27, 28, 31–36, 40, 41] and the secondary endpoint in 5 studies [29, 30, 37–39].

Finally, although it is beyond the purpose of the review, two studies [32, 33] provided a quantitative assessment of image quality. They are the only two studies published in 2017. All the others are older.

Discussion

The large variability in both the physical/technical features of the CBCT-units—especially tube voltage, tube current, exposure time, and FOV—and the different methods used to measure or estimate the effective dose produced significant differences in the dosimetric values, thus making analysis of the results somewhat difficult. Furthermore, since the description of the exposure parameters and scanning protocols was often incomplete, realising the reasons for the different results on the effective dose was hard.

Analysis of dosimetry systems for calculating the effective dose

TLDs inserted in a RANDO phantom represent the conventional reference method for assessing the effective dose. Nevertheless, TLDs need to be replaced within the phantom after every exposure.

Table 2 Non-dental CBCT applications. Anatomical areas, physical and technical features of the CBCT-units, and effective dose

Study	Anatomical area	CBCT-unit												Effective dose (μSv)
		Model	X-ray emission type	Degrees of rotation	Scan diameter (cm)	Scan length (cm)	Reconstruction FOV (AP, LL×CC) (cm×cm)	Voxel side (mm)	Tube current (mA)	Scan time (s)	Exposure time (s)	Current ×exposure time (mAs)	Tube voltage (kV)	
Koivisto et al. [40]	Knee	Planmed Verity[a]	Pulsed	210	13	16	13×16	NA	7.5	NA	6.0	45.0	80	5.6
													84	7.2
													88	8.3
													90	9.4
													92	9.9
													96	12.6
Koivisto et al. [35]	Ankle	Planmed Verity[a]	Pulsed	210	13	16	13×16	0.20	8.0	NA	6.0	48.0	90	6.0
		NewTom 5G[g]	Pulsed	360	18	16	18×16	0.30	0.6	NA	3.6	2.3	110	1.9
					15	12	15×12	0.30	1.5	NA	3.6	5.3	110	4.0
					12	8	12×8	0.15	11.0	NA	5.4	59.0	110	14.3
Ludlow et al. [36]	Foot and ankle	PedCAT[b]	Pulsed	NA	35	20	35×20	0.37	NA	19	4.3	4.5	100	2.6
											4.3	4.5	120	3.8
											6.5	6.8	120	5.8
					20	20	20×20	0.37	NA	19	4.3	4.5	100	1.4
											4.3	4.5	120	2.3
											6.5	5.6	120	2.7
											6.5	6.8	120	3.7
					10	10	10×10	0.37	NA	19	4.3	4.5	120	0.9
Pugmire et al. [37]	Foot and ankle	Planmed Verity[a]	Pulsed	210	NA	NA	NA	NA	NA	NA	NA	NA	NA	13
Koskinen et al. [38]	Wrist	Planmed Verity[a]	Pulsed	210	13	16	13×16	0.40	8.0	18	NA	NA	88	7
de Charry et al. [39]	Radius	NewTom 5G[g]	Pulsed	NA	NA	8	5×5	0.075	NA	28	NA	NA	110	≈10
Nardi et al. [32]	Cervical spine	NewTom 5G[g]	Pulsed	360	18	16	18×16	0.30	NA	18	NA	13.08	110	248
	Ear	NewTom 5G[g]	Pulsed	360	15	5	15×5	0.15	NA	36	NA	141.92	110	361
Zou et al. [31]	Ear	Planmed[e]	Pulsed	NA	6	6	6×6	0.2	11	NA	15	165	88	35.2*, 45.9[♯]

Table 2 (continued)

Study	Anatomical area	CBCT-unit												Effective dose (μSv)
		Model	X-ray emission type	Degrees of rotation	Scan diameter (cm)	Scan length (cm)	Reconstruction FOV (AP, LL×CC) (cm×cm)	Voxel side (mm)	Tube current (mA)	Scan time (s)	Exposure time (s)	Current ×exposure time (mAs)	Tube voltage (kV)	
											22.5	247.5	88	70.4*, 91.7[♯]
											45	495	88	105.6*, 138[♯]
									2	NA	35	NA	70	7.35*, 9.7[♯]
Peltonen et al. [30]	Ear	3D Accuitomo[f]	NA	360	4	3	4×3	0.125	2	NA	17.5	NA	70	13
Ruivo et al. [29]	Ear	i-CAT[d]	Pulsed	360	NA	NA	NA	0.2	NA	20	NA	46.72	120	80
Faccioli et al. [28]	Ear	Maxiscan[g]	Pulsed	360	NA	NA	NA	NA	NA	NA	NA	226.13	110	110
Dierckx et al. [27]	Ear	NewTom 5G[g]	Pulsed	360	15	5	15×5	NA	NA	36	NA	145	110	400^, 190[†]
					12	8	12×8	NA	NA	36	NA	NA	110	290[†]
	Paranasal sinuses	NewTom 5G[g]	Pulsed	360	15	12	15×12	NA	NA	18	NA	27.5	110	100^, 90[†]
					18	16	18×16	NA	NA	36	NA	NA	110	110[†]
Almashraqi et al. [33]	Paranasal sinuses	i-CAT[d]	Pulsed	NA	13	10	13×10	0.25	5.0	NA	4.0	20.0	120	130
								0.30	5.0	NA	4.0	20.0	120	109
								0.30	5.0	NA	2.0	10.0	120	65
Al Abduwani et al. [34]	Paranasal sinuses	Carestream 9300[c]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	270
Bacher et al. [41]	Paranasal sinuses	i-CAT[d]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	30

A available, *NA* no available, *AP, LL, CC* antero-posterior, latero-lateral, and cranio-caudal diameters. Size of AP and LL was equal

^Effective dose measured by dosimeters in combination with a phantom

[†]Effective dose calculated by Monte Carlo simulations

*Magnification of 1.4

[♯]Magnification of 1.7

[a]Planmed Oy, Helsinki, Finland

[b]CurveBeam Inc., Warrington, PA, USA

[c]Carestream Health Inc., Rochester, NY, USA

[d]Imaging Sciences International, Hatfield, PA, USA

[e]Planmed, Helsinki, Finland. It was a Planmeca Oy high-resolution acquisition system

[f]Morita, Kyoto, Japan

[g]QR, Verona, Italy

Since several exposures are recommended to attain more reliable dosimetric values, measuring the effective dose by TLD is very laborious, time-consuming, and prone to mistakes. To overcome these limitations, MOSFET dosimeters have been introduced lately. MOSFETs are purely electronic dosimeters connected to a reader that transfers data to a computer. They can perform multiple real-time measurements without having to repeatedly disassemble and reposition the phantom. The drawback of MOSFETs is that they are visible on the radiographs and produce a heel effect [42, 43].

OSLDs consist of crystals whose electrons collect the energy released from X-rays. At the dosimeter readout, the crystal is stimulated with a light-emitting diode, allowing the electrons to fall back to their original energy state while emitting a characteristic light proportional to the amount of the absorbed radiation dose. OSLDs have a small size and can be positioned on the patient skin. Although several considerations and conditions—such as beam energy and spectrum, dose range, geometrical arrangement, and reading protocol—theoretically warrant the use of specific correction factors, these factors and the related uncertainties are mostly in the single-digit per cent in the typical conditions of medical diagnostic CT. The most significant practical correction factor (easily determinable) may be the one to account for the beam average kV. Contrary to the perception by some, signal fading is not a significant issue over a period of several days or weeks if the OSLDs are handled properly [44, 45].

CTDI and DAP are radiation dose outputs that indicate the amount of radiation directed towards the patient and allow one to compare the radiations of different CT systems. Three papers [37–39] under the current review used a scanner output to calculate the effective dose of extremities by using conventional X-ray conversion factors. CTDI calculates the dose by a pencil ionisation chamber that is only 100 mm long. Therefore, it neither detects the scattered dose over this length nor collects the primary beam in CBCT with a large FOV [46]. The DAP measures the radiation dose to air (without backscatter) multiplied by the area of the X-ray field.

The Monte Carlo simulation is a software-based technique used to simulate photon interactions with living matter since it tracks the trajectories of each individual photon and calculates the amount of energy released point by point. Monte Carlo algorithms are very demanding in computational resources and may require a long time to be performed (depending on the computing power). Although up to 10^9 photons can typically be simulated with the computing power of current hardware and software resources, CT examinations involve a larger number of photons (up to 10^{16} photons). This may limit the accuracy of the dose estimations [47]. The only paper [27] which compared Monte Carlo simulations and TLD, while keeping unchanged all CBCT-unit scanning parameters, found that Monte Carlo simulations underestimated the effective dose by more than 50% in the ears study and by 10% in the paranasal sinuses study, with respect to TLD.

Radiation dose of extremities and cervical spine

Knee

Koivisto et al. [40] used MOSFET dosimeters inserted in a custom-made RANDO phantom. They did not alter the exposure settings, except for the tube voltage, which was changed from 80 to 96 kV with a proportionate increase in the effective dose from 5.6 to 12.6 μSv.

Ankle

Koivisto et al. [35] and Ludlow et al. [36] used three different CBCT-units and two different dosimeters (MOSFET e OSLD) inserted in a custom-made RANDO phantom. Seven different FOVs with variable exposure time, mAs, and kV resulted in effective doses from 0.9 to 14.3 μSv. Pugmire et al. [37] calculated the effective dose of 13 μSv in the paediatric human ankle using the DAP-to-effective dose conventional X-ray conversion factors [48]; however, no CBCT-unit physical/technical parameter was reported.

Wrist

Koskinen et al. [38] and de Charry et al. [39] calculated effective doses of 7 μSv and approximately 10 μSv in adult human wrist and cadaveric distal radius using the DAP- and CTDI-to-effective dose wrist conventional X-ray conversion factors [49], respectively.

The overall mean effective dose for the studies on the extremities was 7.1 μSv.

Cervical spine

Nardi et al. [32] measured the effective dose of 248 μSv by using TLDs in combination with an Alderson-RANDO phantom.

Radiation dose of ear and paranasal sinuses

Ear

Dierckx et al. [27], Nardi et al. [32], Faccioli et al. [28], and Ruivo et al. [29] examined the ear by using TLDs inserted in an Alderson-RANDO phantom. The resulting effective doses were 400, 361, 110, and 80 μSv, respectively. The

Table 3 Non-dental CBCT applications. Features of the dosimetry systems used to calculate effective dose

Study	Anatomical area	Dosimetric study	Method to estimate radiation dosage	Dosimeter					Object			
				Type	Model	Number	Reader	Position	Type	Model	Number of slice	Exposures [*n*]*
Koivisto et al. [40]	Knee	Primary endpoint	Dosimeter	MOSFET[a]	TN-RD-70-W20	20	TN-RD-16	A	Custom-made RANDO phantom	Anthropomorphic leg	8	4
Koivisto et al. [35]	Ankle	Primary endpoint	Dosimeter	MOSFET[a]	TN-RD-70-W20	20	TN-RD-16	A	Custom-made RANDO phantom	Anthropomorphic leg	6	4 to 10
Ludlow et al. [36]	Foot and ankle	Primary endpoint	Dosimeter	OSLD[b]	Nanodot	21	MicroStar[b]	A	Custom-made RANDO phantom	Anthropomorphic leg	6	Multiple
Pugmire et al. [37]	Foot and ankle	Secondary endpoint	Conversion factor from DAP	–	–	–	–	–	Paediatric human bone	–	–	–
Koskinen et al. [38]	Wrist	Secondary endpoint	Conversion factor from DAP	–	–	–	–	–	Adult human bone	–	–	–
de Charry et al. [39]	Radius	Secondary endpoint	Conversion factor from CTDI	–	–	–	–	–	Adult cadaveric bone	–	–	–
Nardi et al. [32]	Cervical spine, Ear	Primary endpoint	Dosimeter	TLD[c]	LiF:Mg,Ti	74	Harshaw 5500[c]	A	Alderson-RANDO Phantom[i]	Male anthropomorphic head and neck	12	1
Zou et al. [31]	Ear	Primary endpoint	Dosimeter	MOSFET[a]	TN-RD-70-W20	20	NA	NA	RAN 102-RANDO Phantom[i]	Male anthropomorphic head	10	10
Peltonen et al. [30]	Ear	Secondary endpoint	NA	–	–	–	–	–	Adult cadaveric bone	–	–	–
Ruivo et al. [29]	Ear	Secondary endpoint	Dosimeter	TLD	NA	166	NA	NA	Alderson-RANDO Phantom	Male anthropomorphic[f]	NA	7
Faccioli et al. [28]	Ear	Primary endpoint	Dosimeter	TLD[h]	GR200A LiF	46	PCL3[e]	A	Alderson-RANDO Phantom[j]	Anthropomorphic head[f]	NA	NA
Dierckx et al. [27]	Ear, Paranasal sinuses	Primary endpoint	Dosimeter	TLD[d]	LiF:Mg,Cu,P	190	Harshaw 5500[c]	A	Alderson-RANDO Phantom[i]	Male anthropomorphic head and neck	15	Multiple
			Monte Carlo	–	–	–	–	–	–	–	–	–

Table 3 (continued)

Study	Anatomical area	Dosimetric study	Method to estimate radiation dosage	Dosimeter					Object			
				Type	Model	Number	Reader	Position	Type	Model	Number of slice	Exposures [*n*]*
Almashraqi et al. [33]	Paranasal sinuses	Primary endpoint	Dosimeter	TLD	LiF:Mg,Ti	42	Alnor Dosacus[f]	A	Alderson-RANDO Phantom[j]	Anthropomorphic head[♯]	10	2
Al Abduwani et al. [34]	Paranasal sinuses	Primary endpoint	Monte Carlo	–	–	–	–	–	–	–	–	–
Bacher et al. [41]	Paranasal sinuses	Primary endpoint	Dosimeter	TLD[d]	NA	156	Harshaw 3500 [g]	NA	Alderson-RANDO Phantom[i]	Anthropomorphic[♯]	NA	10

A available, *NA* no available

*Repetition of acquisition for each dosimeter

[♯]Detailed data of the phantoms were not available

[a]Best Medical, Ottawa, Ontario, Canada

[b]Landauer, Inc., Glenwood, IL, USA

[c]Harshaw Chemical Company, Solon, OH, USA

[d]TLD Poland, Krakow, Poland

[e]Fimel, Vélizy, France

[f]Mirion Technologies, Turku, Finland

[g]Thermo electron, Solon, OH, USA

[h]Central Research Laboratory, Beijing, China

[i]Radiation Analogue Dosimetry System, The Phantom Laboratory, Salem, NY, USA

[j]Alderson Research Laboratories, Stanford, CN, USA

first two aforementioned authors [27, 32] used a large FOV including both ears, whereas the other two authors [28, 29] did not mention the size of the FOV. Dierckx et al. [27] also used Monte Carlo simulations, obtaining an effective dose that was less than half compared to the effective dose measured by TLD. Zou et al. [31] used MOSFET dosimeters and a small FOV; they changed the exposure time and found that the effective dose varied from 7 to 138 µSv. Peltonen et al. [30] reported an effective dose of 13 µSv in the cadaveric temporal bone without specifying the dosimetry system and adapting a dental CBCT-unit with a small FOV.

The overall mean effective dose for the studies on the ear was 178.2 µSv.

Paranasal sinuses

Dierckx et al. [27] measured the effective dose via a specific FOV (15 × 12 cm) for the paranasal sinuses study using both TLDs inserted in an Alderson-RANDO phantom and Monte Carlo simulations. The effective dose was 100 and 90 µSv, respectively. They also estimated the effective dose of 110 µSv using a larger FOV (18 × 16 cm) by Monte Carlo simulations. Almashraqi et al. [33] investigated the paranasal sinuses by TLDs inserted in an Alderson-RANDO phantom. They used a slightly smaller FOV (13 × 10 cm) than Dierckx, and changed both the voxel size (0.25 or 0.30 mm) and the exposure time (2 or 4 s). The effective dose varied from 65 to 130 µSv. Al Abduwani et al. [34] and Bacher et al. [41] estimated effective doses of 270 and 30 µSv by using Monte Carlo simulations and TLDs, respectively, without mentioning any protocol parameter. The overall mean effective dose for the studies on the paranasal sinuses was 119.0 µSv.

Among all the aforementioned authors, only Nardi et al. [32] and Almashraqi et al. [33] provided a quantitative assessment of image quality that represents a key element which should be associated with a dosimetric study. In fact, each physical/technical parameter of every CBCT-unit must be optimised in order to limit the exposure, reach a diagnostically acceptable image quality in relation to the clinical query, and allow the comparison of doses using different imaging techniques.

The ear study requires a high resolution to detect the tiny structures of which it is constituted; consequently, a high radiation dosage is needed [32]. The dose can be generally reduced in the paranasal sinuses, cervical spine, and extremities studies, where the image quality is adequate even with low-dose protocols [32, 33, 50]. Low-dose protocols should be set in all imaging techniques with ionising radiation, especially in CBCT, because of several units with extremely variable acquisition parameters and therefore very different exposures, as shown in the current review. The parameter optimisation has already been discussed in dental CBCT, but further research shall be carried out in non-dental CBCT applications. Furthermore, although CBCT is considered to be a low-dose volumetric imaging technique, in clinical practice the repetition rate of examinations due to motion artefacts is not insignificant (0.9–5.4%) [12, 51, 52]; this increases the mean radiation dose administered to patients.

Overall, the mean CBCT effective dose for the extremities (7.1 µSv) was a little more than double and seven times the amount of one projection X-ray effective dose for the knee (3.0 µSv) [40] and the foot–ankle (1.0 µSv) region [35, 36], respectively. The study of extremities by radiographs needs more than one plain film, and a bone fracture is not always detectable by two-dimensional medical imaging because of the geometric distortion effect and the superimposition of three-dimensional complex skeletal structures [53, 54]. Therefore, we suppose that CBCT may sometimes replace a conventional X-ray examination in extremity bone trauma turned into a first-level imaging since CBCT assures high diagnostic accuracy in the detection of bone fractures [55–58] with an acceptable radiation dose.

Using a standard RANDO phantom or a computational patient model has important limitations because neither system takes into account the constitutional nature of any individual patient and the wide range of scan protocols. It is incorrect to employ a one-size-fits-all phantom to accurately estimate the dose to all patients. In fact, a typical adult phantom does not represent an individual patient-specific habitus; consequently, it will underestimate the dose for a paediatric patient and overestimate the dose for an obese patient because the X-ray beam is attenuated to a greater extent in large patients than in small patients [59].

We noticed that the physical/technical parameters necessary to make the value of an effective dose meaningful were reported more thoroughly in the studies in which the primary endpoint was represented by a dosimetric study. We firmly believe that an accurate report of the effective dose must always be combined with a detailed description of both the physical/technical parameters of any unit and the dosimetry system adopted. Otherwise, the value of the effective dose has poor relevance as it is not reproducible. Similarly, reporting only the scanner output value is not appropriate since scanner outputs are not a real measurement of the patient dose, not unless they are combined with the conversion factors, taking into account the patient's size/age/gender, irradiated organ, body composition, scan range, mAs, and tube voltage [60–62].

Currently, there are no conversion factors for non-dental CBCT. Therefore, using dental CBCT conversion factors is technically inaccurate since they concern a different anatomical area with different tissues and organs irradiated. Even more so, it is debatable to use the conversion factors of different technology systems as conventional X-rays or

multislice CT. For that reason, future investigations on non-dental CBCT conversion factors are recommended.

We wonder whether it is proper to report the scanner output value for the estimation of patient dose in the radiology report as required by the latest international provisions. Scanner outputs do not take into account of variability in tissue weights; therefore, they are an unreliable surrogate for patient dose. We think that mentioning the scanner output value in the radiology report is just the first step towards monitoring both the exposure to the population and the dose to the individual patient. It is desirable for the future to achieve a fast, easy, accurate, cost-effective, and unambiguous system for estimating the effective dose since dosimeters cannot be placed within the organs of a human being. The ideal solution to ensure reliable patient dose measurements would be to have every CT-unit displaying the effective dose directly on the computer screen at the end of each examination by innovative software Monte Carlo simulation-like or reliable conversion factors in combination with scanner outputs. This is a hard challenge for research.

The main limitation of our study was the impossibility of making a meta-analysis because of both the heterogeneity of the methods used to estimate the dose and the limited papers available on the various non-dental CBCT applications. A further limitation was discarding all papers that did not relate to the effective dose, even though they were related to dosimetry. Furthermore, although effective dose represents the most reliable metre used to track the dose for individual patients, effective dose is believed not to be an excellent parameter of patient risk per se [63–65] and the stochastic radiation damage may be underestimated [66, 67].

Conclusions

The current review proved that CBCT of the extremities, cervical spine, ears, and paranasal sinuses was a low-dose volumetric imaging technique. Nevertheless, the effective dose varied considerably among authors due to both the large number of different exposure settings of the several CBCT-units and the various dosimetry systems represented by scanner outputs, Monte Carlo simulations, and different kinds of dosimeters associated with RANDO phantom. Therefore, further studies are required to make the measurement methods uniform with more reliable and consistent estimations of the effective dose values.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical standards This article does not contain any studies with human participants or animals performed by any of the authors.

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