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FULL PAPER

# Effective dose of cone beam CT (CBCT) of the facial skeleton: a systematic review

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**Objective:** To estimate effective dose of cone beam CT (CBCT) of the facial skeleton with focus on measurement methods and scanning protocols.
**Methods:** A systematic review, which adhered to the preferred reporting items for systematic reviews (PRISMA) Statement, of the literature up to April 2014 was conducted. Data sources included MEDLINE®, The Cochrane Library and Web of Science. A model was developed to underpin data extraction from 38 included studies.
**Results:** Technical specifications of the CBCT units were insufficiently described. Heterogeneity in measurement methods and scanning protocols between studies made comparisons of effective doses of different CBCT units and scanning protocols difficult. Few studies related doses to image quality. Reported effective dose varied across studies, ranging between 9.7 and 197.0 μSv for field of views (FOVs) with height ≤5 cm, between 3.9 and 674.0 μSv for FOVs of heights 5.1–10.0 cm and between 8.8 and 1073.0 μSv for FOVs >10 cm. There was an inconsistency regarding reported effective dose of studies of the same CBCT unit with the same FOV dimensions.
**Conclusion:** The review reveals a need for studies on radiation dosages related to image quality. Reporting quality of future studies has to be improved to facilitate comparison of effective doses obtained from examinations with different CBCT units and scanning protocols. A model with minimum data set on important parameters based on this observation is proposed.
**Advances in knowledge:** Data important when estimating effective dose were insufficiently reported in most studies. A model with minimum data based on this observation is proposed. Few studies related effective dose to image quality.


Since introduction in the late 1990s, cone beam CT (CBCT) has become a common modality to image the facial skeleton. There is currently a large variety of CBCT units on the market,[1,2] and technical improvements are made continuously, such as the development of the field of view (FOV) from one fixed size to several sizes as well as stitched FOVs in the more recent models.

The use of CBCT has increased dramatically, but published evidence supporting informed clinical decision-making is weak.[1] As is the case with emerging healthcare technologies, it will take some time to produce evidence on the cost-effectiveness of CBCT for different diagnostic tasks including "costs" in terms of radiation dosages. Meanwhile, the use of CBCT and choice of scanning protocol has to rely on good practice related to the image quality needed for the actual diagnostic task and the amount of radiation exposure to the patient. The literature on dose levels of CBCT is, however, difficult to grasp and interpret owing to the diversity of CBCT units and different approaches taken in radiation dosimetry.

The aim of this systematic review was to estimate the effective dose of CBCT of the facial skeleton with focus on measurement methods and scanning protocols used. Such a review can be beneficial when aiming to perform CBCT examinations with a radiation exposure as low as diagnostically acceptable (ALADA).[3] A review may also highlight both strengths and weaknesses in study design to date and can thereby support sound study design in future research.

## METHODS AND MATERIALS

The literature review was conducted in accordance with the preferred reporting items for systematic reviews (PRISMA) Statement[4] and guidance of Centre for Reviews and Dissemination for undertaking reviews in healthcare.[5] The following steps were defined: (i) review questions, (ii) literature searches, (iii) study selection and (iv) data extraction and synthesis.

## REVIEW QUESTIONS

Regarding CBCT of the facial skeleton, the review questions were as follows:

– Which methods and scanning protocols were used when measuring and estimating the radiation dosage?
– What are the effective doses?

The following terms were based on Medical Subject Headings (MeSH):

– CBCT/instrumentation: CT modalities that use a cone- or pyramid-shaped beam of radiation.
– Facial bones: the facial skeleton, consisting of bones situated between the cranial base and the mandibular region. While some consider the facial bones to comprise the hyoid (hyoid bone), palatine (hard palate), zygomatic (zygoma) bones, mandible and maxilla, others include also the lacrimal and nasal bones, inferior nasal concha and vomer but exclude the hyoid bone.
– Radiation dosage as stated above defined according to MeSH.
– Thermoluminescent dosimetry as stated above defined according to MeSH.

The following terms not included in MeSH were defined as:

– Dental CT: CBCT used for the oral and maxillofacial region.
– Effective dose according to International Commission on Radiation Protection (ICRP) publication 103:[6] the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body.
– Material to measure radiation dosages: dosemeters and read-outs.
– Scanning protocols: exposure parameters and phantom features.

## LITERATURE SEARCHES

The searches were designed together with university librarians. The search strategies are presented in Table 1. The following electronic databases were searched: MEDLINE® using PubMed as search engine, the Web of Science and the Cochrane Database of Systematic Reviews in The Cochrane Library. The search in MEDLINE was based on MeSH terms and free-text terms. The searches in Web of Science and The Cochrane Library (the Cochrane Database of Systematic Reviews) were performed using free-text terms. Additional hand search was carried out using the reference lists of retrieved systematic reviews.

## STUDY SELECTION

Eligibility assessment of half of the retrieved titles and abstracts was performed independently by two authors, and two other authors assessed the other half of the titles and abstracts. When at least one of the authors regarded a record as having met the inclusion criteria, it was ordered and read in full text. Reviewers were not blinded to authors and institutions of the records during the study selection process.

The inclusion criteria were

– Publication type: original study or systematic review.
– CBCT unit: described regarding brand and version, FOV dimensions, degree of rotation, X-ray beam type (pulsed or continuous radiation).
– Anatomical region: facial region, further detailed and described in studies of FOVs ≤10 cm.
– Material: equipment to measure radiation dosage (dosemeters and read-outs).
– Outcomes: data on effective dose based on ICRP 60—1990[7] or ICRP 103—2007[6]
– Language: abstract in English and full-text publication in English, German or Japanese.

## DATA EXTRACTION AND DATA SYNTHESIS

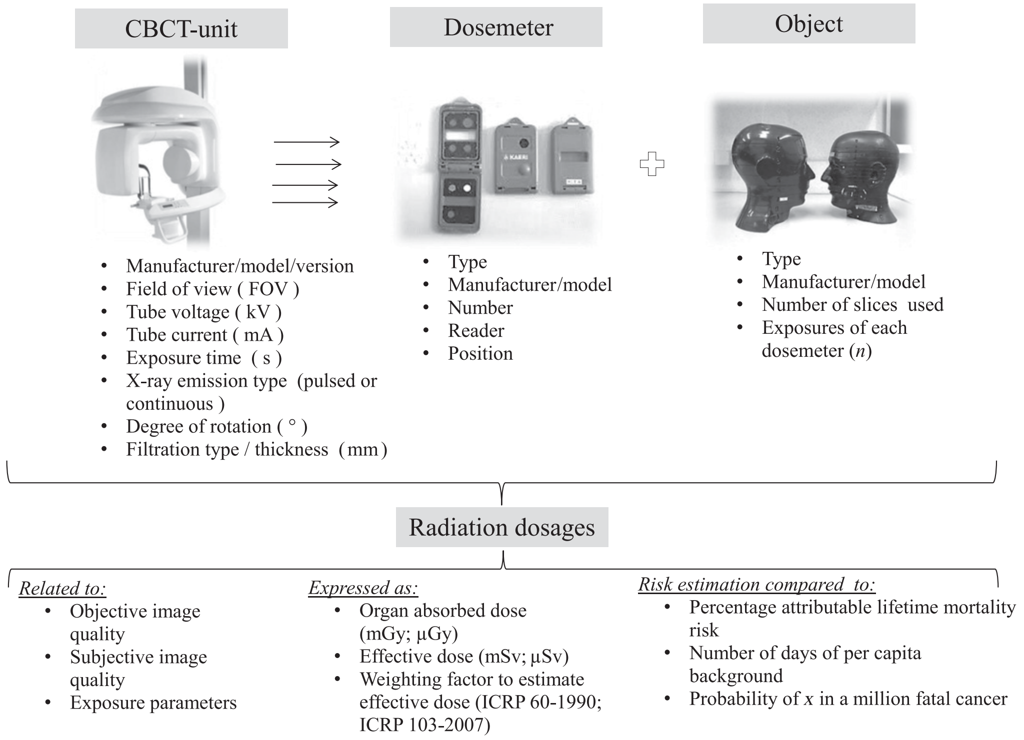
We developed a model with components that were considered important when performing studies of radiation dosages in CBCT (Figure 1) and a data extraction sheet. Information was extracted from each study on (i) the CBCT unit(s), (ii) method to measure and estimate radiation dosages, (iii) scanning protocol, (iii) object and (iv) radiation dosages. When information of the CBCT unit was insufficient, information was searched for on the manufacturer's website. Together, the authors pilot tested the data extraction sheet on five included studies. The authors had different professional backgrounds and experience: one radiophysicist, two specialists (>25 years' experience) and two trainees in oral and maxillofacial radiology. One author

Table 1. Search strategies and number of publications retrieved from MEDLINE®, the Web of Science and the Cochrane Library

| Indexing terms | Publications ($n$) |
|---|---|
| MEDLINE | |
| #1 Cone Beam Computed Tomography (MeSH) | 3150 |
| #2 Cone Beam Computed Tomography | 4968 |
| #3 Dental CT | 4727 |
| #4 Radiation Dosage (MeSH) | 67,196 |
| #5 Radiation Dosage | 110,803 |
| #6 Thermoluminescent Dosimetry (MeSH) | 2873 |
| #7 Thermoluminescent Dosimetry | 3274 |
| #8 = #1 OR #2 | 4968 |
| #9 = #8 OR #3 | 9226 |
| #10 = #4 OR #5 | 110,803 |
| #11 = #6 OR # 7 | 3274 |
| #12 = #10 OR #11 | 112,099 |
| #13 = #9 AND #12 | 737 |
| Web of Science | |
| Topic = (Radiation Dosage) OR Topic = (Thermoluminescent Dosimetry) AND Topic = (Cone Beam Computed Tomography) | 3000 |
| Refined by: Web of Science Categories = (DENTISTRY ORAL SURGERY MEDICINE) | 92 |
| The Cochrane Library | |
| There are 6 results from 783,686 records for your search on "(Radiation Dosage OR Thermoluminescent Dosimetry) AND Cone Beam Computed Tomography in title abstract keywords in Trials" | 6 |

MeSH, Medical Subject Headings.
Search conducted on the 22 April 2014.

Figure 1. A model presenting the steps for data extraction with different parameters important when analysing radiation dosages in cone beam CT (CBCT) of the facial skeleton. FOV, field of view; ICRP, International Commission on Radiation Protection.




extracted data from included studies, and the other authors checked the extracted data independently. Disagreement was resolved by discussion.

Effective doses for three heights of FOV (≤5 cm, 5.1–10.0 cm and >10.0 cm) were compiled in a spreadsheet. Median values, 25 and 75 percentiles, and range for effective dose values were calculated using software (Microsoft Office Excel® 2010; Microsoft Corporation, Redmond, WA).

## RESULTS

### Study selection

Figure 2 shows the number of publications identified, excluded and included. Of the retrieved publications, 674 were discarded because, after reviewing the abstracts, it appeared that these publications did not meet the inclusion criteria. The full text of the remaining 67 publications was examined, and 38 met the inclusion criteria. Three systematic reviews were excluded because their research question was different to that of the present review, but an additional three studies were identified and included by checking the reference lists of these reviews. Most included studies were published from 2008 onwards, the number of studies being the highest in 2008 and 2012.

### Methods and scanning protocols used to measure and estimate radiation dosages

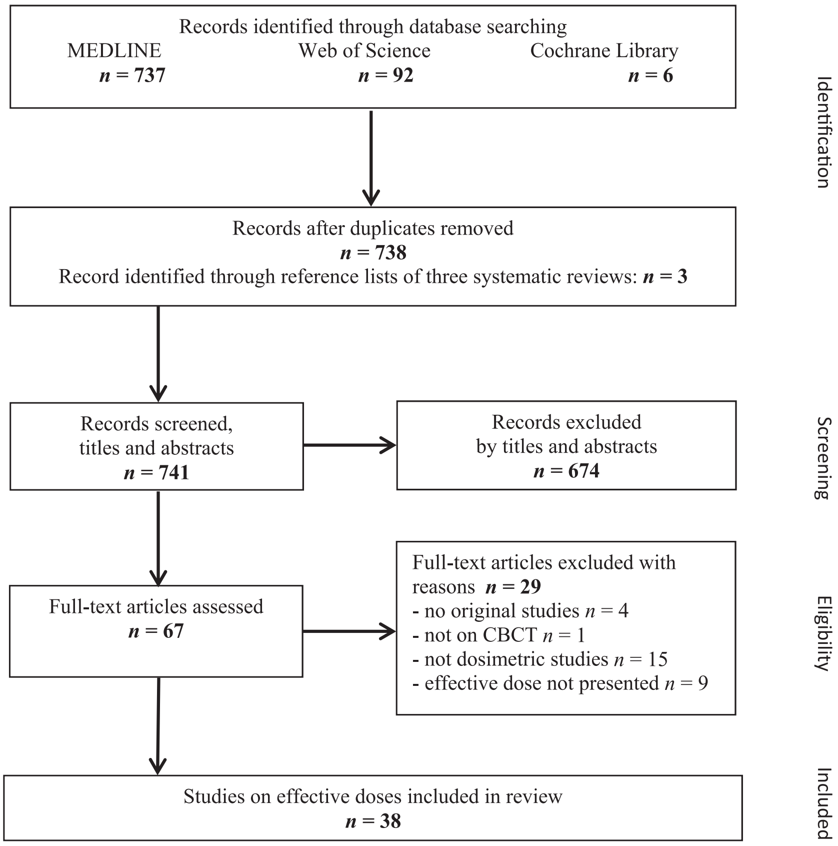
The methods used to measure radiation dosages varied across the studies (Table 2). The following methods were used: thermoluminescent dosemeter (TLD) 100 (25 studies), TLD-100H (8 studies), optically stimulated luminescence dosemeter (OSLD) (2 studies), radiochromic film (2 studies), ionization chamber (2 studies), magnesium orthosilicate doped with terbium ($Mg_2SiO_4$:Tb; TLD-MSO-S) (1 study), lithium borate ($Li_2B_4O_7$)-TLD (1 study) and photoluminescence glass (1 study). Also, the type of phantom, the number of slices, dosemeters and exposures of each dosemeter varied across studies (Table 2). In most studies, a commercially available anthropomorphic phantom including an adult male skull was used. A phantom that included a female skull was examined in three studies and a paediatric phantom (corresponding to a person 10 years of age) in two studies. In two studies, the phantom was developed at the institution (University of Göttingen, Göttingen, Germany) where the study was performed. Only in one study[40] was the phantom repositioning between scans described in enough detail to ascertain reproducibility. The method for distribution of dosemeters as described by Ludlow et al[27] was applied in most studies. The number of phantom slices ranged between 7 and 10 and the number of TLDs was about 24 in most studies. The number of exposures of dosemeters ranged between 1 and 10, except for 1 study using 34 exposures.[44] In seven studies, there was no information about the number of TLDs, and in one-third of the studies there was no information about the number of exposures of dosemeters.

Complete technical specifications of the CBCT unit were described in only one study.[40] Supplementary information, such as the degree of rotation or trajectory arc, filtration and detector specifications, was partly accessible on the manufacturers' websites.

### What are the effective doses of cone beam CT examinations of the facial skeleton?

Effective doses and individual study characteristics are presented in Supplementary Tables A–C. In seven studies, ICRP 1990 and

Figure 2. Flow chart according to the preferred reporting items for systematic reviews (PRISMA) statement[4] presenting study selection process with number of publications identified, excluded and included for systematic review of effective dose of cone beam CT (CBCT) of the facial skeleton.




ICRP 2007 weights were presented so that the effect of the change from 1990 weights to 2007 in effective dose calculations could be estimated. The increase of the estimated effective dose using 2007 compared with 1990 was on average 173% (range, 58–350) for FOVs with height ≤5 cm, 164% (range, 64–276) for FOVs 5.1–10.0 cm and 76% (13–180) for FOVs with height >10 cm.

As presented in Figure 3, effective dose was influenced by the height of the FOV. The reduction of the median effective dose of FOVs with height 5.1–10.0 cm compared with that of FOVs with height >10 cm was 38%. The reduction of the median effective dose of FOVs with height ≤5 cm compared with that of FOVs with height 5.1–10.0 cm was 59%. The maximum effective dose of the smallest FOVs overlapped the median dose of the FOVs with height 5.1–10.0 cm and the same applied to the FOVs of medium and large heights (Figure 3). The ranges between the highest and lowest doses of each FOV height were wide (Figure 3). As presented in Figure 4, there was a variation in reported dose estimates for the same CBCT unit with the same FOV dimensions.[10,14,20,25,35,39] As the description of technical parameters of the CBCT units examined was incomplete, it was difficult to evaluate which components of the CBCT units that produced the different results on effective doses in these studies. Besides, different phantoms, dosemeter types and number, exposure parameters and protocols were applied in these studies (Figure 4).

In addition to the size, the positioning of the FOV influenced the effective dose. The dose of FOVs of <10 cm was higher for examination of the lower jaw than for the upper jaw[23,30] and for examinations with the FOV positioned on the posterior part of the lower jaw than for the anterior part of the upper jaw.[14,38,45] The effective dose was reduced by 43% when 0.4-mm copper filtration was added in examinations with FOV heights 9 and 18 cm.[18]

Effective dose was related to image quality in six studies (Table 2) expressed as objective image quality[21,32,39,40] or subjective image quality.[17,19] As presented in Table 2, the effective dose of CBCT was compared with those of other imaging modalities in eight studies: CT,[13,16,24,25,37,44] panoramic radiography[16,25,31,37,44,45] and cephalometry.[37] Risk estimations were presented in eight studies[12,18,23,25,27,30,35,45] mostly as comparisons with background radiation.

## DISCUSSION

This systematic review revealed that key methodological details of measurement methods and scanning protocols were missing. We did not implement any quality evaluation in this systematic review, as there is no validated tool for this publication type, as is the case for quality evaluation of diagnostic studies. If the model proposed in Figure 1 had been used as a quality tool, all but one study[40] would have been excluded, as technical data of the CBCT units was insufficiently described.

Table 2. Methodology for measurements and estimation of the radiation dosage in cone beam CT (CBCT) of the facial skeleton

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number ($n$) | Exposures of each dosemeter ($n$) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used ($n$) | | |
| TLD-100 | | | | | | |
| Kim et al[8] | 22 | NA | – ART head and neck phantom (Radiology Support Devices, Inc., Long Beach, CA)<br>– Adult male | 9 | – Equivalent organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | Conversion coefficients from the DAP |
| Schilling and Geibel[9] | 24 | – Prescan 50<br>– Scan 3 | – Alderson RANDO® ART-210 (Radiology Support Devices, Inc.)<br>– Adult male | 9 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | Organ absorbed dose from middle ranges for each unit |
| Rottke et al[10] | 48 | 10 | – RANDO head phantom (The Phantom Laboratory, Salem, NY) | 8 | – NA<br>– Effective dose<br>– ICRP 2007 | |
| Davies et al[11] | 72 | 10 | – RANDO head (The Phantom Laboratory)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Grünheid et al[12] | 24 | 3 | – RANDO (The Phantom Laboratory)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 2007 | |
| Jeong et al[13] | 3 × 25 | NA | – ART (Radiology Support Devices, Inc.)<br>– Adult | 16 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | Compared with CT with low-dose technique |
| Pauwels et al[14] | 147; 152 | NA | – Two ART head and neck phantom (Radiology Support Devices, Inc.)<br>– Adult male | 11 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | |
| Rampado et al[15] | 50 | 10 | – RANDO head phantom (The Phantom Laboratory) | 9 | – NA<br>– Effective dose<br>– ICRP 2007 | |
| Sezgin et al[16] | 21 | NA | – RANDO head phantom | NA | – NA<br>– Effective dose<br>– ICRP 2007 | Compared with panoramic radiography and CT |

(Continued)

Table 2. (Continued)

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number ($n$) | Exposures of each dosemeter ($n$) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used ($n$) | | |
| Librizzi et al[17] | 78 | 3 | – RANDO (The Phantom Laboratory) | NA | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | Image quality assessed as presence or absence of erosion of temporomandibular joint by two radiologists |
| Ludlow[18] | 24 | 9 or 10 | – RANDO (Nuclear Associates, Hicksville, NY)<br>– Adult | 7 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | Doses with and without 0.4-mm copper filtration |
| Carrafiello et al[19] | 42 | NA | – RANDO (Alderson Research Laboratories, Inc., New York, NY) | 10 | – NA<br>– Effective dose<br>– ICRP 1990 | Subjective image quality: analysed spongy bone, teeth, surrounding structure and soft tissues<br>Assessed on five-point scale by two observers |
| Qu et al[20] | 63 | 5 | – ART phantom, model ART-210 (Radiology Support Devices, Inc.)<br>– Adult male | 7 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Faccioli et al[21] | 46 | NA | – RANDO (Alderson Research Laboratories, Stanford, CN)<br>– NA | NA | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | Image quality assessed as high and low contrast resolution, uniformity and noise |
| Loubele et al[22] | NA | 10 | – Two RANDO (Alderson Research Laboratories, NY)<br>– Male | 20 | – NA<br>– Effective dose<br>– ICRP 2007 | |
| Roberts et al[23] | 72 | 10 | – RANDO<br>– Adult | 8 | – NA<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Coppenrath et al[24] | Unclear | NA | – RANDO | NA | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990 | Compared with CT |
| Ludlow and Ivanovic[25] | 24 | 3 | – RANDO (Nuclear Associates)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 1990, 2007 | Compared with CT and average panoramic dose |

(Continued)

Table 2. (Continued)

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number ($n$) | Exposures of each dosemeter ($n$) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used ($n$) | | |
| Palomo et al[26] | 10 | 1 | – RANDO head phantom (The Phantom Laboratory) | 7 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Ludlow et al[27] | 24 | 3 | – RANDO (Nuclear Associates)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 1990, 2005 draft recommendations | |
| Wörtche et al[28] | NA | NA | – RANDO | NA | – NA<br>– Effective dose<br>– ICRP 2005 draft recommendations | |
| Tsilakis et al[29] | 25 | NA | – RANDO (Alderson Research Laboratories, CN) | NA | – NA<br>– Effective dose<br>– ICRP 1990, ICRP 1990 + salivary glands | |
| Ludlow et al[30] | NA | 10 | – RANDO (Nuclear Associates)<br>– Small adult | 7 | – NA<br>– Effective dose<br>– ICRP 1990, ICRP 1990 + salivary glands | |
| Mah et al[31] | NA | 2 | – Humanoid, tissue-equivalent dosimetry phantom (Humanoid Systems Inc., Torrance, CA) | NA | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990 | Compared with panoramic radiography and CT |
| Cohnen et al[32] | 26 | 2 | – RANDO | 13 | – NA<br>– Effective dose<br>– NA | Image quality assessed as mean image noise |
| TLD-100H | | | | | | |
| Davies et al[11] | 72 | 10 | – RANDO (The Phantom Laboratory)<br>– Male | 7 | – NA<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Pauwels et al[14] | 147; 152 | NA | – Two ART head and neck phantom (Radiology Support Devices, Inc.)<br>– Adult male | 11 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | Different numbers of TLDs used for two phantoms |

(Continued)

Table 2. (Continued)

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number ($n$) | Exposures of each dosemeter ($n$) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used ($n$) | | |
| Qu et al[33] | 3 chips Positioned at 21 locations (3 × 21) | 5 | – Anthropomorphic ART-210 (Radiology Support Devices, Inc.)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 2007 | Evaluated influence of thyroid collars |
| Qu et al[34] | 63 | 5 | – Anthropomorphic ART-210 (Radiology Support Devices, Inc.)<br>– Adult male | 7 | – NA<br>– Effective dose<br>– ICRP 2007 | Different oral and maxillofacial regions with and without thyroid collar |
| Theodorakou et al[35] | 10 years: 104<br>Adolescents: 140 | NA | – ATOM® model 702-c, 706-c (Computerized Imaging Reference System Inc., Norfolk, VA) | 10 years: 10<br>Adolescent: 11 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 2007 | |
| Loubele et al[22] | NA | 10 | – Two RANDO (Alderson Research Laboratories, NY)<br>– Male | 20 | – NA<br>– Effective dose<br>– ICRP 2007 | TLD-100H used for organs and tissues expected to receive low dose |
| Hirsch et al[36] | 48 | 5 | – Anthropomorphic (developed at University of Göttingen, Göttingen, Germany) | 16 sites | – Mean absorbed dose<br>– Effective dose<br>– ICRP 2007 | |
| Silva et al[37] | 48 | 5 | – Anthropomorphic (developed at University of Göttingen) | NA | – NA<br>– Effective dose<br>– ICRP 2007 | Compared with panoramic radiography, lateral cephalometry and CT |
| TLD-MSO-S | | | | | | |
| Okano et al[38] | 132 | 2 | – RANDO<br>– Female body phantom | All | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | |
| Lithium borate ($Li_2B_4O_7$)-TLDs | | | | | | |
| Suomalainen et al[39] | 26 | NA | – RANDO (Nuclear Associates) and RSVP Phantom™ (The Phantom Laboratory, Salem, NY) | NA | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | Image quality assessed as CNR and MTF |

(Continued)

Table 2. (Continued)

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number (*n*) | Exposures of each dosemeter (*n*) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used (*n*) | | |
| Optically stimulated luminescence dosemeter | | | | | | |
| Ludlow and Walker[40] | 24 | 2–12 exposures | – ATOM Max model 711 HN and ATOM model 706 HN (Computerized Imaging Reference System Inc.)<br>– Adult male and 10-year-old child | 9 | – Equivalent organ dose<br>– Effective dose<br>– ICRP 2007 | Image quality assessed as contrast, homogeneity, CNR, MTF, polymethylmethacrylate voxel and noise, Nyqvist frequency |
| Lukat et al[41] | 25 | 3 | – RANDO (Alderson Research Laboratories, CT)<br>– Male | 7 | – Equivalent organ dose<br>– Effective dose<br>– ICRP 2007 | |
| Ionization chamber | | | | | | |
| Vassileva and Stoyanov[42] | Not applicable | NA | – NA | NA | – NA<br>– Effective dose<br>– ICRP 1990, 2007 | Air kerma–area product |
| Lofthag-Hansen et al[43] | Not applicable | NA | – For CTDI100: CT head dose phantom type 76-414 (Victoreen Instruments, Cleveland, OH) | NA | – NA<br>– Effective dose<br>– NA | Measurement of radiation exposure<br>Effective dose based on CTDI100<br>Effective dose based on DAP<br>Patient examinations |
| Photoluminescence glass | | | | | | |
| Okano et al[44] | 155 | 3D Accuitomo (J Morita Mfg. Corp., Kyoto, Japan): 100<br>CB MercuRay (Hitachi Medical Corp., Tokyo, Japan): 50 | – RANDO (Alderson Research Laboratories, CT)<br>– Female | 34 | – Organ absorbed dose<br>– Effective dose<br>– ICRP 1990, 2007 | Compared with panoramic radiography and CT<br>34 slices from skull to pelvic bones |

(Continued)

Table 2. (Continued)

| Study | Dosemeter | | Object | | Radiation dosage presented as:<br>– Organ absorbed dose<br>– Effective dose<br>– Weighting factor to estimate effective dose (ICRP 60[7]— 1990; ICRP 103[6]—2007) | Comments |
|---|---|---|---|---|---|---|
| | Number (n) | Exposures of each dosemeter (n) | Phantom<br>– Type (manufacturer)<br>– Size | Slices used (n) | | |
| Radiochromic film | | | | | | |
| Al-Okshi et al[45] | 3–4 sheets | 10–50 | – RANDO (The Phantom Laboratory)<br>– Small adult | 6 | – Organ absorbed dose<br>– Effective dose<br>– CRP 2007 | Compared with panoramic radiography |
| Rampado et al[15] | 50 pieces<br>Width, 5 mm<br>Length, 25 mm | 10 | – RANDO (The Phantom Laboratory) | 9 | – NA<br>– Effective dose<br>– ICRP 2007 | Compared TLD with Gafchromic film (International Specialty Products Corp., Wayn, NJ) |

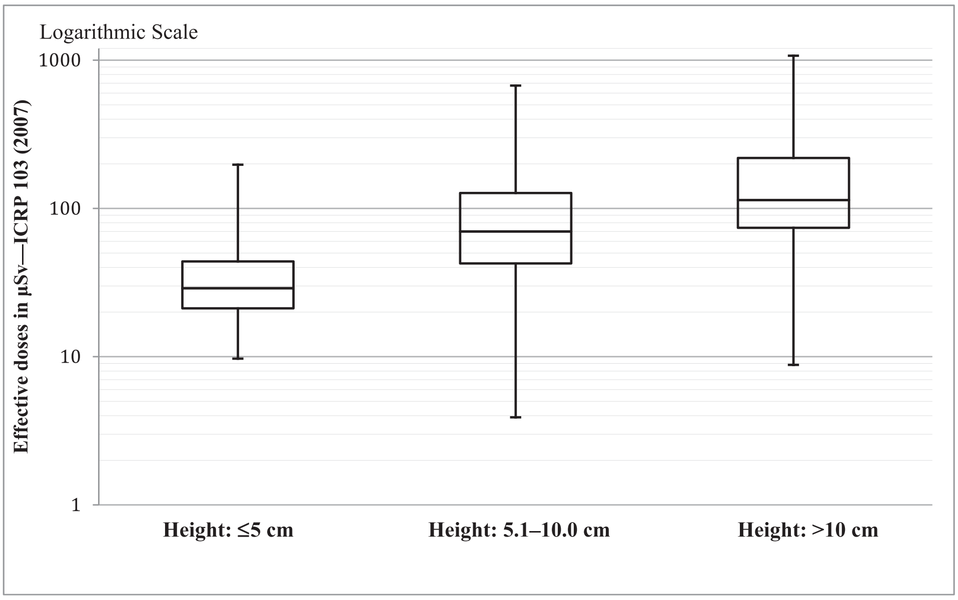
CNR, contrast-to-noise ratio; CTDI, CT dose index; DAP, dose-area product; ICRP, International Commission on Radiation Protection; MTF, modulation transfer function; NA, information not available; TLD, thermoluminescent dosemeter.

TLD-100 was used in most studies, probably owing to the fact that TLD-100 is not only used in the field of dosimetry but also for monitoring personnel radiation doses, which means that the method is a well established clinical routine. The main advantages of the TLD-100 are good sample-to-sample uniformity, nearly tissue equivalent and simple calibration procedures using common radionuclide sources. According to Al Najjar et al,[46] TLDs may be less accurate in the lower dose range than OSLDs, which were used in two recent studies.[40,41] The results of the study by Ludlow and Walker[40] showed, however, that TLDs and OSLDs yielded differences of <2% in the calculation of effective dose in CBCT. Radiochromic film, used in two studies,[15,45] is, compared with TLDs, easier to adjust on the phantom in relation to the radiation field and present a continuous "analog"-like dose distribution, where the limit for spatial resolution is set by the pixel size when digitizing the image in the flatbed scanner.[45] CT dose index (CTDI) or the dose–area product (DAP) in combination with a conversion factor was used in one study.[47] When used for CBCT dosimetry, both CTDI and DAP have been criticized. CTDI underestimates the dose by failing to measure scatter radiation to tissues outside the scan region.[25] DAP value represents only the surface dose and effective doses based on DAP conversion factor have been found to be inaccurate for small FOVs.[43] As revealed by this review, radiation dosages have been measured and estimated with dosimetric methods used in conventional dental radiography, such as intraoral and panoramic radiography, and in CT. There are, however, significant differences between these imaging modalities, for example, dose distribution and scanning geometry, which entail a different approach to measurements of the radiation for CBCT. The shortcoming of the CTDI concept is well known, and the International Atomic Energy Agency[48] and American Association of Physicists in Medicine[49] have proposed recommendations on new CTDI type measurements but, as of yet, there is not any new dosimetry standard established.

The nature and size of the phantom, number of sections and the position and extension of the organs inside the phantom varied across the studies. In most studies, an adult RANDO® anthropomorphic phantom was used but the attenuation varies as each RANDO phantom is constructed around a real human skull or synthetic bone material. A specific phantom has been developed (SedentexCT IQ CBCT Phantom; Leeds Test Object Ltd, Boroughbridge, UK) that has been shown to be valid for assessment of image quality parameters.[50] There were only two studies using a paediatric phantom corresponding to patients aged 10 years.[35,40] This is notable as CBCT is increasingly replacing two-dimensional imaging modalities, such as cephalometry and panoramic radiography, in adolescents aged 10–18 years undergoing orthodontic treatment. As the justification for an increased dose to this young patient group is unclear,[1] there is an urgent need to estimate effective doses in relation to diagnostic tasks when examining these patients.

One known factor influencing effective dose is the dimension of the FOV. If all other factors affecting the dose remain constant, a larger FOV results in a higher dose. The dose

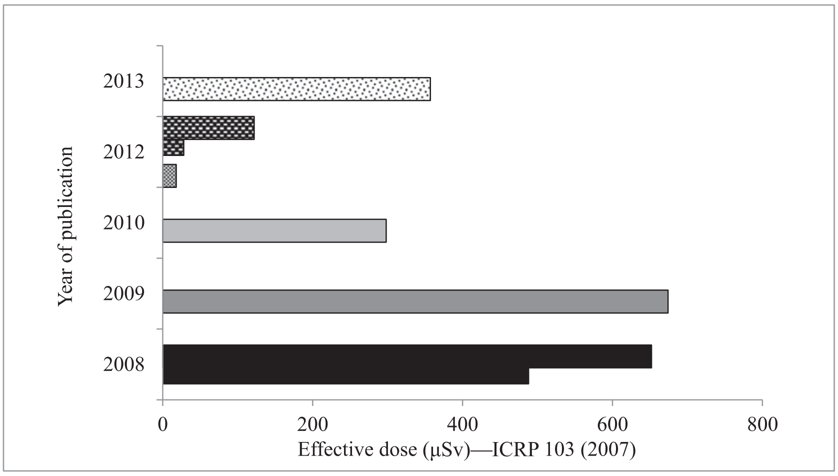
Figure 3. Box and whisker diagram of effective doses (μSv) of cone beam CT units with three heights of fields of view. ICRP, International Commission on Radiation Protection.




| Effective dose (μSv) | Height: ≤5 cm | Height: 5.1–10.0 cm | Height: >10 cm |
|---|---|---|---|
| Minimum | 9.7 | 3.9 | 8.8 |
| Median | 28.5 | 69.9 | 114.0 |
| Maximum | 197.0 | 674.0 | 1073.0 |

range for the same FOV height was wide, which is in line with the results presented in the review by Bornstein et al[51] and overlapped for different FOV heights indicating that several factors influence the effective dose. This was further highlighted in our synthesis of the results of six studies of the same CBCT unit with the same FOV dimensions.[10,14,20,25,35,39] The positioning of FOV with heights ≤10 cm was shown to influence dose such that exposure of the posterior part of the lower jaw resulted

Figure 4. Effective doses (μSv) of different versions of the same cone beam CT unit with the field of view of 8 × 8 cm$^2$ presented in studies published 2008–13. ART, Radiology Support Devices Inc., A Carson, CA; ATOM®, Computerized Imaging Reference System, Norfolk, VA. ICRP, International Commission on Radiation Protection; TLD, thermoluminescent dosemeter.




| Study | Phantom | TLD | Number of TLDs | kV | mA | mAs | Protocol |
|---|---|---|---|---|---|---|---|
| Rottke et al[10] | RANDO® | 100 | 48 | 84 | 16 | | |
| Pauwels et al[14] | ART | 100 + 100H | 147 or 152 | 84 | | 19.9/169.0 | Low/high dose |
| Theodorakou et al[35] | ATOM® | 100H | 40 | 84 | | 19.6 | Adolescent |
| Qu et al[20] | ART | 100 | 63 | 84 | 16 | | |
| Suomalainen et al[39] | RANDO | $LiB_4O_7$ | 26 | 84 | 12 | | |
| Ludlow and Ivanovic[25] | RANDO | 100 | 24 | 84 | | 72/96 | Large adult/small adult |

in higher effective dose than did the anterior part of the upper jaw,[14,38,45] because salivary gland and thyroid tissues receive little exposure when the FOV is centred on the anterior upper jaw.

Since effective dose was related to image quality in few studies, it is difficult to assess how the dose can be reduced and still achieve the diagnostic aims of a CBCT examination. Image quality of rotation of 180° and 360° was compared in examinations of the posterior parts of the jaws, and it was concluded that "a rotation of 180° gave good subjective image quality, hence a substantial dose reduction can be achieved without loss of diagnostic information".[52] It remains, however, to produce more evidence on how the reduction of the scan arc from 360° to 180° in combination with other factors will influence image quality for different diagnostic tasks. As stated by Ludlow and Walker,[40] "As optimization and dose reduction become more of a focus for CBCT manufacturers, the effect on image quality will need close attention."

Our review has limitations. Although the literature search was performed with some language limitation and only in databases, not in reference lists of included studies, some studies were probably missed. However, the search was in accordance with assessment of multiple systematic reviews (AMSTAR),[53] which proposes a search of at least two electronic sources. As the definition of facial skeleton in MeSH guided the study selection, studies of the soft tissues and surrounding regions of the facial skeleton were excluded. Key methodological data of measurement methods and scanning protocols were missing, which made data extraction difficult and might have induced bias. Heterogeneity between how effective doses were measured and calculated in the included studies is likely to have an effect on our calculations of the median values for different FOV heights.

In conclusion, although there were many studies on effective dose of CBCT of the facial skeleton, the quality of the evidence is low on how different diagnostic tasks and appropriate image quality should be matched with different scanning protocols to accord with the ALADA principle. According to grading of recommendations assessment, development and evaluation (GRADE),[54] the quality of evidence is low when there is a limitation to the study quality, important inconsistency of estimates of effects across studies and an uncertainty about important consequences. As this is the case for effective dose in CBCT, further research is very likely to have an impact on our confidence in the estimates of effective doses. For estimations, and in particular comparisons of effective doses of different CBCT units and scanning protocols, a more complete reporting is required. A minimum data, as presented in the model presented in Figure 1, has to be reported in future studies on optimization and image quality of CBCT examinations.

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