RESEARCH ARTICLE

Radiation dose from X-ray examinations of impacted canines: cone beam CT vs two-dimensional imaging

^{1,2}Nils Kadesjö, ^{3,4}Randi Lynds, ⁵Mats Nilsson and ^{1,4}Xie-Qi Shi

¹Department of Dental medicine, Karolinska Institutet, Stockholm, Sweden; ²Medical Radiation Physics, Karolinska University Hospital, Stockholm, Sweden; ³Folktandvården, Stockholm County Council, Stockholm, Sweden; ⁴Department of Clinical Dentistry, University of Bergen, Bergen, Norway; ⁵Medical Radiation Physics, Skåne University Hospital, Malmö, Sweden

Objectives: To compare the radiation dose to children examined for impacted canines, using two-dimensional (2D) examinations (panoramic and periapical radiographs) and cone beam CT (CBCT).

Methods: Organ doses were determined using an anthropomorphic 10-year-old child phantom. Two CBCT devices, a ProMax3D and a NewTom5G, were examined using thermoluminescent dosimeters. For the panoramic radiograph, a Promax device was used and for periapical radiographs, a Prostyle device with a ProSensor digital sensor was used. Both the panoramic and the intraoral devices were examined using Gafchromic-QR2 dosimetric film placed between the phantom slices.

Results: ProMax3D and NewTom5G resulted in an effective dose of 88 µSv and 170 µSv respectively. A panoramic radiograph resulted in an effective dose of 4.1 µSv, while a periapical radiograph resulted in an effective dose of 0.6 µSv and 0.7 µSv using a maxillary lateral projection and central maxillary incisor projection respectively.

Conclusions: The effective dose from CBCT ranged from 140 times higher dose (NewTom5G compared to two periapical radiographs) to 15 times higher dose (ProMax3D compared to three periapical and one panoramic radiograph) than a 2D examination.

Dentomaxillofacial Radiology (2018) 47, 20170305. doi: [10.1259/dmfr.20170305](https://doi.org/10.1259/dmfr.20170305)

Cite this article as: Kadesjö N, Lynds R, Nilsson M, Shi X-Q. Radiation dose from X-ray examinations of impacted canines: cone beam CT vs two-dimensional imaging. *Dentomaxillofac Radiol* 2018; 47: 20170305.

Keywords: impacted canine; effective dose; CBCT; panoramic X-ray; intraoral X-ray

Introduction

An impacted maxillary canine is a common problem in dentistry, with an incidence of 1–5.2%.^{1,2} If a non-erupted canine is not buccally palpable at age 10–11 during clinical observation, diagnosis of an impacted canine requires radiographic examinations. The most acceptable method in current dental practice is periapical radiograph examination, many times combined with panoramic, cephalometric or occlusal radiographs.^{3–7} The limitation of using these methods is that maxillary canines often overlap the incisor's root, making it difficult to assess possible root resorption

in the bucco-palatal direction.^{5,8} The location of the impacted canines in the maxilla presents a clinical challenge when taking intraoral images, as images can be distorted so that three-dimensional (3D) structures may appear superimposed, further complicating diagnostics.^{3,5} When the above-mentioned radiographic examinations cannot provide enough diagnostic information, one should then supplement the examination with localized small volume cone beam CT (CBCT) according to European guidelines.⁹ Compared with conventional radiographic methods such as periapical and panoramic radiographs, the amount of resorption detected by CT and CBCT scanning has been found to be increased by over 50%.^{5,10}

Correspondence to: Nils Kadesjö, E-mail: nils.kadesjo@sl.se

Received 05 August 2017; revised 21 December 2017; accepted 27 December 2017

Nevertheless, the increased spatial information in CBCT images compared to two-dimensional (2D) images is not guaranteed to translate into additional benefit for the patient, *i.e.* the long-term outcome of the treatment. In the absence of long-term follow-ups, an intermediary indication of the benefit would be if the availability of CBCT significantly affects the choice of treatment. However, there is no consensus that CBCT has this effect, and both the British and the European guidelines state that routine CBCT examination is not considered justified.^{9,11} Still, there are some studies showing a significant effect on treatment planning, indicating that CBCT might be justified as routine examination for a subset of the patients examined for impacted maxillary canines.^{5,7,12}

A CBCT examination results in a higher radiation dose compared to panoramic and intraoral radiographs.¹³ When choosing the appropriate radiological examination, both the radiation dose and the clinical benefit to the patient must be considered. Several studies have examined the doses from either CBCT, panoramic or intraoral radiographs for adult patients, usually through thermoluminescent dosimeter (TLD) measurements.^{14–16} However, only a few studies have looked at the doses that children receive.^{17,18} Furthermore, TLD measurements of organ dose and effective dose for intraoral and panoramic radiographs involve very large uncertainties. Dosimetric film has been suggested as a more accurate alternative for these modalities.^{19,20} As far as we know, no study has determined the dose to child patients from all X-ray modalities of interest when specifically diagnosing an impacted canine. The current study aims to determine and compare the dose from both periapical and panoramic radiographs as well as CBCT examinations for children having impacted canines with possible root resorption in neighbouring teeth, using TLD and film measurements.

Methods and materials

X-ray devices

Two CBCT devices were examined, a ProMax3D classic (Planmeca Oy, Helsinki, Finland) and a NewTom5G (QR Srl, Verona, Italy). The CBCT volumes were centred on the anterior maxilla. A ProMax2D (Planmeca) was

used to provide panoramic radiographs, and for intraoral radiographs, a Prostyle with a ProSensor digital sensor (Planmeca) was used. The panoramic radiograph utilized child collimation to reduce the image size and effective dose. For the periapical radiographs two different projections were investigated, a maxillary lateral projection and a central maxillary incisor projection. For all devices, the measurements were performed with higher mAs and multiple exposures in order to obtain a dose suitable to the dynamic range of the dosimeters. The results were then scaled to the clinical exposure settings based on dose-area-product (DAP) measurements. The DAP measurements were performed with a VacuDAP Typ 70 157 transmission ion chamber (VacuTech Meßtechnik GmbH, Dresden, Germany) connected to a DoseGuard electrometer (RTI Electronics AB, Mölndal, Sweden). The parameters used for each radiographic modality and the resulting DAP values are listed in Table 1.

Detectors and phantom

Organ doses from CBCT images (ProMax3D and NewTom5G) were determined from measurements performed with TLD-100 thermoluminescent dosimeters and read with a Harshaw 5500 (Thermo Scientific, Waltham, MA) TLD reader. For the panoramic and intraoral units, as well as the NewTom5G, organ doses were determined from measurements performed with Gafchromic-QR2 dosimetric film (International Speciality Products, Wayne, NJ). All the film used was from the same batch. Both measurement methods were used for the NewTom5G in order to compare the film and TLD measurements. The NewTom5G CBCT unit was chosen for the comparison due to it having the largest X-ray field of all tested X-ray devices and is thus expected to have the least uncertainty caused by detector positioning.

Measurements were taken using an ATOM-706-C paediatric 10-year-old anthropomorphic phantom (CIRS, Norfolk, VA). The phantom is comprised of tissue equivalent epoxy resins and divided into 25 mm thick slices. Within each slice is a 1.5 cm spaced grid of holes for the placement of TLDs. The top 10 slices were used (Figure 1a). The difference between the child and adult phantoms of the ATOM series lies in the size and shape, as well as a difference in the composition of the

Table 1 List of investigated X-ray devices and their corresponding parameters, as well as the resulting DAP

X-ray device	Modality	kV	HVL (mmAl)	mAs	Size ^a (cm)	Voxel/pixel size (mm)	DAP (mGycm ²)
ProMax3D	CBCT	90	8.0	109	4 × 5	0.160	510
NewTom5G	CBCT	110	4.4	72	6 × 6	0.125	1080
ProMax2D	Panoramic	62	2.9	42	19.2 × 9.2	0.096	21.9
Prostyle	Intraoral	66	2.1	0.8	4.5 × 5.5	0.030	7.42

CBCT, cone beam CT; FOV, field of view; DAP, dose-area-product; HVL, half value layer.

^aSize corresponds to FOV for CBCT images, to image size at the focus plane for panoramic images and to collimator cone size for intraoral images.

Figure 1 (a) The paediatric phantom (b) Example of delineation of the organs used for detector placement (c) Film response from the NewTom5G examination (d) Film response from the panoramic examination (e) Film response from the central incisor periapical radiograph (f) Dose map for the periapical examination after background correction, dose-response calibration and sensor attenuation correction. Images b through f correspond to the same phantom slice.

surrogate bone material. In the case of the 10-year-old phantom, the surrogate bone has 3% lower electron density compared to the adult version.

For each phantom slice, the extent of the organs of interest was delineated on transparent film, shown in Figure 1b. With the aid of these organ outlines, TLD measurement points were chosen to cover as homogeneously as possible the volume inside the head and neck region for each organ of interest. The transparent films were also scanned and used to define the organ location for film dosimetry. TLDs were placed at 34 measurement points within the phantom, with two detectors at each site (Table 2, the positioning of each measurement point and Table 3, the number of measurement points used for each organ). The dose at each measurement point were often included in the calculation of the mean organ dose to multiple neighbouring or overlapping organs (Table 2). Dosimetric films were placed between the phantom slices, covering the entire area of the slice.

Calibration and dosimetry

Both the TLDs and the dosimetric film were calibrated for dose to water using the in-air method from the American Association of Physicists in Medicine protocol for 40–300 kV X-ray beam dosimetry.²¹ Cross-calibration was performed using a Victoreen Model 550–4 T (Victoreen, Cleveland, OH) ion chamber, calibrated at the Swedish Secondary Standard Dosimetry

Laboratory. The measurements were then converted into dose to the surrogate tissue *four-component soft tissue* as defined by the International Committee on Radiological Units, using mass energy-absorption coefficient ratios taken from the American Association of Physicists in Medicine protocol previously mentioned.²¹ Dose to International Committee on Radiological Units four-component soft tissue were used for all investigated organs.

Doses outside the head and neck region were considered negligible, and organs only partially positioned inside this region had their average dose multiplied with the fraction of that organ located inside the head and neck region. For active bone marrow, Cristy's distribution for a 10-year-old were used: cranium 11.6%, mandible 1.1% and cervical vertebrae 2.7%.²² Due to a lack of published data on the distribution of endosteum (bone surface) in children, the relation between an adult and a 10-year-old was assumed to be the same as for active marrow. Thus, the fractions were estimated by scaling the adult endosteum distribution in the International Commission of Radiological Protection (ICRP) 110 computational phantom with Cristy's ratio between an adult and a 10-year-old for active marrow, resulting in: cranium 24.9%, mandible 0.6%, cervical vertebrae 1.5%.²³ For the lymphatic nodes, the adult distribution from ICRP 110 was used: 6.3%.²³ The fraction of the oesophagus inside the head- and neck region was estimated

Table 2 Position of the 34 measurement sites

Position	Slice	Contributing to organs
Cranium posterior	2	Active marrow, endosteum, brain
Brain central	2	Brain
Cranium right	2	Active marrow, endosteum, brain
Cranium anterior	2	Active marrow, endosteum, brain
Brain central	3	Brain
Cranium posterior	4	Active marrow, endosteum, brain
Cranium right	4	Active marrow, endosteum, brain
Brain central	4	Brain
Cranium anterior	4	Active marrow, endosteum, brain
Cranium posterior	5	Active marrow, endosteum, brain
Cranium left	5	Active marrow, endosteum, brain
Pituitary	5	Active marrow, endosteum, brain
Parotid gland	6	Salivary glands
Vertebra	6	Active marrow, endosteum
Caput	6	Active marrow, endosteum, salivary glands, lymphatic nodes
Nasopharynx	6	Extrathoracic airways
Palate	6	Oral mucosa
Maxilla	6	Active marrow, endosteum
Vertebra	7	Active marrow, endosteum
Submandibular gland	7	Salivary glands, lymphatic nodes
Oropharynx	7	Extrathoracic airways
Mandible right	7	Active marrow, endosteum
Mucosa left	7	Oral mucosa
Sublingual gland	7	Salivary glands, lymphatic nodes, oral mucosa
Mandible anterior	7	Active marrow, endosteum
Vertebra	8	Active marrow, endosteum
Oesophagus	8	Oesophagus
Lymph node cervical	8	Lymphatic nodes
Hypopharynx	8	Extrathoracic airways
Vertebra	9	Active marrow, endosteum
Thyroid lobe	9	Thyroid
Thyroid isthmus	9	Thyroid
Oesophagus	10	Oesophagus
Lymph node supraclavicular	10	Lymphatic nodes

The thermoluminescent dosimeters were placed near the described structure and included in one or several adjacent organs.

at 10%. Effective dose was calculated for each image according to the ICRP 103 tissue weighting factors, listed in [Table 3](#).²⁴

Film readout

The dosimetric film was read with an Epson Perfection 7000 flat-bed scanner (Seiko Epson Corporation, Suwa, Japan) in reflection mode and saved as 24-bit RGB TIFF images with 200DPI. The images were analysed in ImageJ (National Institutes of Health, Bethesda, MD). The red colour channel was separated and used

Table 3 The tissue weighting factor for each of the organs included and the number of TLD measurement sites contributing to the mean organ dose

Organ	Weighting factor	Number of TLD sites
Active marrow	0.12	17
Endosteum	0.01	17
Brain	0.01	11
Extrathoracic airways	0.12/13	3
Lymphatic nodes	0.12/13	5
Oral mucosa	0.12/13	3
Salivary glands	0.01	4
Thyroid	0.04	2
Oesophagus	0.04	2

TLD, thermoluminescent dosimeter.

for dosimetry since the film's sensitivity is highest in this channel. Because the signal-to-dose response of Gafchromic film is non-linear, dose-response calibration curves are needed.^{25,26} This calibration was done individually for each X-ray device by a fourth-degree polynomial fit of the signal-to-dose relation. The polynomial fit was obtained from film exposed at seven different dose levels between 1 and 120 mGy.

During the phantom measurements, a non-irradiated background film was handled in the same way and read at the same time as the measurement film. The film signal was defined as the difference in pixel value compared to the mean value of the background film. The dose-response calibration was then applied on a pixel-by-pixel basis to calculate the dose. Organ doses were determined as the mean dose of all the pixels within the delineated organ area. For intraoral radiographs, a correction for the X-ray attenuation within the intraoral sensor was applied. In the area shielded by the detector, the dose was multiplied by the transmission through the sensor ([Figure 1f](#)). The transmission of the sensor was estimated at 4.5%.²⁰

Results

The absorbed dose for each organ of interest and image is shown in [Table 4](#). Some organ doses (brain dose from panoramic and thyroid dose from periapical radiographs) were below the sensitive dose range of the film. The resulting effective dose for each image is shown in [Table 5](#). Depending on the patient's dental status, a complete 2D examination could range from two periapical radiographs with different lateral maxillary projections to an examination of bilateral impaction consisting of three periapical radiographs, two lateral projections and one central incisor projection, plus one panoramic radiograph to obtain an overview of the tooth development status. The sum of the effective dose from these examinations resulted in an effective dose ranging from 1.2 µSv to 6 µSv respectively. The effective dose from ProMax3D and NewTom5G were 88 µSv and about 170 µSv respectively.

Table 4 Mean organ dose (μGy) for different radiographic examinations determined from TLD or film measurements

Organ	Mean organ dose (μGy)					
	<i>ProMax3D</i> (TLD)	<i>NewTom5G</i> (TLD)	<i>NewTom5G</i> (film)	<i>Panoramic</i> (film)	<i>Periapical lateral</i> (film)	<i>Periapical central</i> (film)
Active marrow	130	270	230	1.8	1.2	1.7
Endosteum	190	430	350	1	0.5	0.5
Brain	510	760	560	–	0.3	0.2
Extrathoracic airways	1400	2200	2700	72	6.2	1.6
Lymphatic nodes	94	160	160	11	0.3	0.4
Oral mucosa	2600	5800	4800	66	30	35
Salivary glands	1800	3800	2900	160	5.5	6
Thyroid	200	340	680	17	–	–
Oesophagus	36	34	75	6.1	0.5	1.4

TLD, thermoluminescent dosimeter.

In case no dose is presented, the signal was below the sensitive dose range of the film throughout the entire organ. For panoramic radiographs this corresponds to below 20 μGy and for periapical radiographs this corresponds to below 6 μGy .

The comparison between TLD and film measurements showed an excellent agreement in the resulting effective dose. Effective dose for a NewTom5G image was 172 μSv when calculated from the TLD measurements, compared to 166 μSv calculated from the film measurements. The deviation between individual organ doses determined from TLD and film measurements is illustrated in Figure 2. For most organs, the agreement was good, within approximately $\pm 25\%$. However, for the thyroid and oesophagus, the deviation was large, about 100% and 120% respectively.

Discussion

The investigated CBCT devices resulted in an examination with a much higher effective dose than that from a periapical or a panoramic X-ray examination. The specific extent of the total dose increase depends on the patient's dental status, and the resulting choice of periapical and panoramic radiographs taken. In the case of a unilateral impacted canine, if a CBCT volume was obtained instead of two periapical radiographs, the estimated effective dose would be about 70 or 140 times higher depending on the choice of CBCT device. In the case of a bilateral investigation, where a

CBCT volume was obtained instead of three periapical radiographs, the estimated effective dose would be about 45 or 90 times higher depending on the CBCT device. On the furthest end dose-wise, if a panoramic radiograph is prescribed as a supplement for diagnosing bilateral impacted canines, the effective dose from a CBCT examination would be about 15 or 30 times higher than that from the 2D X-ray examinations. Due to this large increase in radiation dose, clinicians need to be informed when prescribing CBCT examinations for children with impacted canines. CBCT examinations should be restricted to cases where it might affect the treatment. Therefore, it is important to be able to identify patients with impacted canines in whom the

Table 5 Effective dose (μSv) for each of the radiographic images, with effective dose for NewTom5G calculated both from TLD measurements and film measurements

Type of examination	Effective Dose (μSv)
ProMax 3D (TLD)	88
NewTom 5G (TLD)	172
NewTom5G (film)	166
Panoramic (film)	4.1
Periapical lateral maxillary (film)	0.6
Periapical central incisor (film)	0.7

TLD, thermoluminescent dosimeter.

Figure 2 Deviation between organ doses from NewTom5G measured with film and measured with TLDs. TLD, thermoluminescent dosimeter.

CBCT findings change therapeutic thinking. A CBCT examination increases the amount of root resorption detected compared to intraoral and panoramic radiographs.^{4,5,27} However, there is no consensus whether this increased detection rate affects the treatment plan or not. Some studies found significant changes.^{5,7} Others found no significant changes.^{27,28} Of special interest is a study by Christell *et al.*, where out of 12 patient cases only one case showed significant change in treatment planning based on CBCT and panoramic radiographs, compared to periapical and panoramic radiographs.¹² However, for this single case, characterized by severe space deficiency, the change in treatment planning was very large. Based on periapical radiographs 20 of 39 orthodontists chose to extract the permanent canine and 2 orthodontists chose to extract the lateral incisor, based on CBCT the corresponding numbers were 3 of 39 and 31 of 39 respectively. The authors concluded that while only a subgroup might benefit from CBCT, with further research there is potential to possibly identify selection criteria for CBCT.

An accurate diagnosis based on proper clinical and radiographic evaluation is critical for the successful treatment of tooth impaction. When conventional intraoral radiography does not supply adequate information for therapeutic planning, a localized CBCT is indicated.⁹ In this case, adequate image quality CBCT scans are needed in order to accurately localize impacted canines and their proximity to surrounding structures as well as to assess possible resorption of adjacent teeth and the presence of other pathologies. The current study employed the default protocol of ProMax3D for impacted canines applied at Karolinska Institutet. The exposure parameters for the NewTom5G were determined automatically, since this device makes use of automatic exposure control. For both CBCT devices, small voxel sizes were applied to ensure adequate image quality for resorption assessment. While the present study uses “full dose” exposure protocols, Hildago Rivas *et al.* have investigated the possibility of using low dose exposure protocols for impacted maxillary canines in children.²⁹ They used the 3D Accuitomo F170 (J Morita, Kyoto, Japan) to obtain images of an anthropomorphic phantom constructed from a child skull with an impacted canine, submerged in water. Images were obtained at different kV and mAs, using 4×4 cm field of view (FOV) images with 0.08 mm voxel size. Eight observers rated the images to identify the optimized exposure level, resulting in an optimized DAP of 146 mGycm², about half the DAP of the manufacturers recommended exposure protocol. This is a good indication of where an optimized exposure level might lie, but further research using several different phantoms or real patient cases is needed to verify the protocol. Additionally, the optimized exposure level will vary somewhat between CBCT models. Compared to the current study, this optimized DAP is low. However, a large part of this difference is explained by the availability of smaller FOV

for the 3D Accuitomo F170. This stresses the need for small FOV options for paediatric and localized CBCT examinations, but complicates the comparison of exposure levels. A better comparison of the exposure levels would be the DAP divided by FOV, resulting in 26 mGy for ProMax3D and 30 mGy for NewTom5G compared to 9.1 mGy for the optimized Accuitomo F170 protocol. The results of Hildago Rivas *et al.* indicate the possibility to use lower dose levels than in the present study. Nevertheless, even if the CBCT doses are reduced to a third so as to match the optimized protocol, the difference to periapical and panoramic doses is still large, confirming that the need to restrict the use of CBCT to cases where it may affect the treatment still holds true.

The process of estimating organ dose through dosimetric measurements involves large uncertainties. Non-standardized organ boundaries, a limited number of measurement points, and the distribution of organ mass are all especially problematic factors for small X-ray field analysis, which is often the case in dental radiology. Still, dose measurements using anthropomorphic phantoms and TLD have long been established within dentomaxillofacial radiology.^{14–16} An alternative method, using self-developing radiographic film, has also been used more recently.^{19,20,30} Compared to point measurements, such as TLD, film dosimetry has the advantage of allowing for high resolution continuous measurements over a large area, thus making it suitable for dosimetry in panoramic and intraoral radiographs. The use of discreet measurement points is unsuitable for examinations with pronounced dose gradients in the transverse plane, such as panoramic radiographs, due to the large uncertainties in determining the mean organ dose.¹⁹ In this case, film dosimetry is preferred. Film dosimetry also provides advantages in determining the organ dose in the case of intraoral radiographs, where dose measurements are complicated by the presence of the detector inside the oral cavity as well as the small X-ray field size.²⁰ The sharp dose gradients for panoramic and intraoral radiographs, compared to CBCT, are illustrated in [Figure 1](#). Therefore, we used film dosimetry for these two modalities instead of TLD measurements. In order to validate the film measurements compared to TLD, both methods were used with the NewTom5G. Although the dose distribution from the Newtom 5G is more homogenous compared to intraoral and panoramic radiographs, some deviations between the methods are still expected due to the TLD measurement points not being placed exactly even within the delineations of the organs. The deviation is further increased by misalignment in the *z*-direction: the film is placed between the slices while the TLDs are placed in the middle of the slice, 12.5 mm below the film. When the organ of interest is placed completely inside the primary X-ray field, the *z*-direction misalignment is expected to result in only minor deviations between the two methods. However, for organs that are completely, or mostly, outside the primary field, the deviation is

expected to be large. The attenuation of the scattered radiation through one slice of 25 mm of tissue equivalent plastic is about 50%. This was verified by comparing the film measurements between slices; in both the case of the slices being above and the case of the slices being below the X-ray field, an exponential fit of the results showed a dose reduction of 45% per slice. Using this exponential fit for half a slice (12.5 mm) the attenuation is 33%, giving an expected deviation between film and TLD of -33% superior to and +49% inferior to the primary X-ray field. The brain, and to a lesser extent the endosteum and the active marrow, are positioned mostly superior to the X-ray field. As such, the film measurements are expected to show a lower result when compared to the TLD, somewhere between -33% and 0%. The deviations between the two methods (from -26% for the brain to -15% for the active marrow) are within this expected range. No clear trend in the deviation between the methods can be seen for the organs mostly placed within the primary field (airways, lymphatic nodes, oral mucosa and salivary glands). In this case, the deviation ranged between +23% and -24%. The magnitude of this deviation between measurement methods is normal when compared to previously published variations in the determined organ dose from using different numbers of TLDs.¹⁶ The last group of organs, consisting of the thyroid and the oesophagus, is completely positioned inferior to the primary X-ray field. Thus, the film measurements are expected to give about 49% higher dose than the TLD measurements. However, the actual measurements showed a larger deviation between the methods: 100% for the thyroid and 120% for the oesophagus. This results in a deviation of 33 and 47% respectively after the attenuation is corrected for, as illustrated in Figure 3. It is not clear why the oesophagus and the thyroid showed larger deviation from the expected value than the other organs. It should be noted, however, that these organs are more susceptible to various measurement errors due to the low signal outside the primary X-ray field and due to the low number of TLD measurement points.

The dose below the head and neck region was assumed to be negligible, and thus only this part of the phantom was used. This has been standard practice within dentomaxillofacial radiology since at least the early measurements by Ludlow and until today, including the thorough SEDENTEXCT dose study.^{16,31} Similar practice have been used for child phantoms.^{17,18} Due to the smaller size of child phantoms, a larger fraction of the scattered radiation might reach sensitive organs outside the head and neck region. However, this fraction will still be very small compared to the fluence inside the primary beam, due to the attenuation within the phantom as well as the general reduction of the fluence with distance from the primary beam. To estimate the systematic error introduced by neglecting the dose below the head and neck, we might extrapolate the dose according to the 45% attenuation per slice shown

Figure 3 The deviation between organ doses from NewTom5G measured with film and TLDs, after correcting thyroid dose and oesophagus dose for the 12.5 mm offset between film and TLD. TLD, thermoluminescent dosimeter.

above. For this estimation, we averaged the dose inside two regions: the upper part of the thorax (approximately the area between the thyroid and the heart) and the lower part of the thorax (approximately the area including the heart and ending at the diaphragm). The upper part of the thorax was estimated to contribute 7.6% weight to the effective dose (4% lungs, 1.2% oesophagus, 0.92% thymus, 1.5% active marrow) while the lower part of the thorax was estimated to contribute 23.6% weight (8% lungs, 1.2% oesophagus, 0.92% heart, 12% breasts, 1.5% active marrow). Extrapolating from the dose at the thyroid, the resulting mean dose to the upper thorax and lower thorax respectively was the following: 56 μ Sv and 5.1 μ Sv respectively for Promax3D, 94 μ Sv and 8.6 μ Sv respectively for NewTom5G (TLD), 4.7 μ Sv and 0.43 μ Sv respectively for the panoramic radiograph. This would in turn result in the following increase in the effective dose: 6.2% for Promax3D, 5.4% for NewTom5G and 11% for the panoramic radiograph. Although organs inside the abdomen and pelvis contribute about 50% of the weight to the effective dose, the negligible fraction of the scattered radiation reaching these organs will result in less than 1% increased effective dose.

The calculations above are rough estimates and the values should not be taken as scientifically proven. For instance, they don't include the increased attenuation inside the spine and lower attenuation inside the lungs. However, they show that a reasonable estimate of the error introduced by only including the head and neck part of the 10-year-old phantom is about 5 to 15%. This error will not substantially affect the comparison between the different modalities. Performing

measurements of the scattered radiation outside the head and neck area would require hundreds of exposures to obtain accurate detector readings. This is not recommended as a time efficient way to improve the accuracy of the effective dose. Instead, it is important to include enough measurement points inside the head, as shown by the SEDENTEXCT dose study.¹⁶

While effective dose should never be used to estimate cancer risk to an individual, it is still useful for optimization and comparing different technologies for the same examination.^{24,32} Effective dose was used to estimate and compare the radiation risk between the different X-ray examinations of children. This approach of employing effective dose has regularly been used for child patients.^{17,18} However, effective dose is not specifically defined for children and may cause misleading results because the same tissue weighting factors are used for the entire population regardless of age. Radiation sensitivity varies with age, with children being more sensitive than adults. Additionally, the sensitivity variation is not consistent among different tissues. Thus, for an accurate risk assessment, specific tissue weighting factors are needed for different ages. The limitations in the effective dose concept have led to arguments for the need of an age-specific risk-quantity based on cancer incident data: an “effective risk”.³³ There are available cancer-risk data, such as the United States Environmental Protection Agency “Blue Book”.³⁴ However, this data is limited to certain types of cancer. Of the cancer types relevant to the head and neck region, only data for thyroid, leukaemia and bone cancer is available. In the current study, a major part of the dose was to the salivary glands, oral mucosa, extrathoracic airways and brain. Due to the lack of age-specific risk data for these

organs, effective dose was chosen for the risk comparison as the alternatives were deemed to be equally or more misleading. If comprehensive age-specific risk data becomes available in the future, it would be appropriate to instead calculate the age-specific risk from the organ doses presented.

In conclusion, the effective dose from one CBCT examination of an impacted canine was much higher than corresponding 2D examinations. The effective dose was between 70 and 140 times higher than a unilateral examination comprised of two periapical radiographs. In the case of a bilateral examination comprised of three periapical radiographs plus one panoramic radiograph, the effective dose from one CBCT examination was between 15 and 30 times higher. Due to this large increase in dose, CBCT examinations are only justified for cases where it might affect the treatment of the patient. Further research is needed to identify selection criteria for these cases.

Acknowledgments

We thank the Christie Medical Physics and Engineering, The Christie NHS Foundation Trust for providing the paediatric phantom used in the study.

Funding

This work was supported by grants provided by the Stockholm County Council (ALF project) as well as grants provided by the Steering Committee at Karolinska Institutet and Stockholm County Council for Odontology Research (SOF project).

References

- Kramer RM, Williams AC. The incidence of impacted teeth. A survey at Harlem hospital. *Oral Surg Oral Med Oral Pathol* 1970; **29**: 237–41.
- Dachi SF, Howell FV. A survey of 3,874 routine full-mouth radiographs. *Oral Surgery, Oral Medicine, Oral Pathology* 1961; **14**: 1165–9. doi: [https://doi.org/10.1016/0030-4220\(61\)90204-3](https://doi.org/10.1016/0030-4220(61)90204-3)
- Alqerban A, Jacobs R, Lambrechts P, Loozen G, Willems G. Root resorption of the maxillary lateral incisor caused by impacted canine: a literature review. *Clin Oral Invest* 2009; **13**: 247–55. doi: <https://doi.org/10.1007/s00784-009-0262-8>
- Alqerban A, Jacobs R, Fieuws S, Willems G. Comparison of two cone beam computed tomographic systems versus panoramic imaging for localization of impacted maxillary canines and detection of root resorption. *Eur J Orthod* 2011; **33**: 93–102. doi: <https://doi.org/10.1093/ejo/cjq034>
- Botticelli S, Verna C, Cattaneo PM, Heidmann J, Melsen B. Two-versus three-dimensional imaging in subjects with unerupted maxillary canines. *Eur J Orthod* 2011; **33**: 344–9. doi: <https://doi.org/10.1093/ejo/cjq102>
- Guerrero ME, Shahbazian M, Elsiens Bekkering G, Nackaerts O, Jacobs R, Horner K. The diagnostic efficacy of cone beam CT for impacted teeth and associated features: a systematic review. *J Oral Rehabil* 2011; **38**: 208–16. doi: <https://doi.org/10.1111/j.1365-2842.2010.02141.x>
- Haney E, Gansky SA, Lee JS, Johnson E, Maki K, Miller AJ, et al. Comparative analysis of traditional radiographs and cone-beam computed tomography volumetric images in the diagnosis and treatment planning of maxillary impacted canines. *Am J Orthod Dentofacial Orthop* 2010; **137**: 590–7. doi: <https://doi.org/10.1016/j.ajodo.2008.06.035>
- Koye V, Gröndahl HG. Characteristics of patients referred for Cone Beam Computed Tomography (CBCT) of ectopically erupting maxillary canines. *Swed Dent J* 2011; **35**: 159–65.
- European Commission. Radiation protection 172: Cone beam CT for dental and maxillofacial radiology. In: *Evidence Based Guidelines*; 2012.
- Ericson S, Kurol PJ. Resorption of incisors after ectopic eruption of maxillary canines: a CT study. *Angle Orthod* 2000; **70**: 415–23. doi: [https://doi.org/10.1043/0003-3219\(2000\)070<0415:ROI-AEE>2.0.CO;2](https://doi.org/10.1043/0003-3219(2000)070<0415:ROI-AEE>2.0.CO;2)
- Husain J, Burden D, McSherry P, Morris D, Allen M. Clinical Standards Committee of the Faculty of Dental Surgery, Royal College of Surgeons of England National clinical guidelines for management of the palatally ectopic maxillary canine. *Br Dent J* 2012; **213**: 171–6. doi: <https://doi.org/10.1038/sj.bdj.2012.726>
- Christell H, Birch S, Bondemark L, Horner K, Lindh C. SEDENTEXCT consortium The impact of Cone Beam CT on financial costs and orthodontists' treatment decisions in the management

- of maxillary canines with eruption disturbance. *Eur J Orthod* 2017; doi: <https://doi.org/10.1093/ejo/cjx039>
13. European Commission Cone Beam CT for Dental and Maxillofacial Radiology: Evidence Based Guidelines. *Radiation Protection Publication* 2012; **172**.
14. Looe HK, Eenboom F, Chofor N, Pfaffenberger A, Steinhoff M, Rühmann A, et al. Conversion coefficients for the estimation of effective doses in intraoral and panoramic dental radiology from dose-area product values. *Radiat Prot Dosimetry* 2008; **131**: 365–73. doi: <https://doi.org/10.1093/rpd/ncn172>
15. Ludlow JB, Davies-Ludlow LE, Brooks SL, Howerton WB. Dosimetry of 3 CBCT devices for oral and maxillofacial radiology: CB Mercuray, NewTom 3G and i-CAT. *Dentomaxillofac Radiol* 2006; **35**: 219–26. doi: <https://doi.org/10.1259/dmfr/14340323>
16. Pauwels R, Beinsberger J, Collaert B, Theodorakou C, Rogers J, Walker A, et al. SEDENTEXCT Project Consortium Effective dose range for dental cone beam computed tomography scanners. *Eur J Radiol* 2012; **81**: 267–71. doi: <https://doi.org/10.1016/j.ejrad.2010.11.028>
17. Theodorakou C, Walker A, Horner K, Pauwels R, Bogaerts R, Jacobs R. SEDENTEXCT Project Consortium Estimation of paediatric organ and effective doses from dental cone beam CT using anthropomorphic phantoms. *Br J Radiol* 2012; **85**: 153–60. doi: <https://doi.org/10.1259/bjr/19389412>
18. Davis AT, Safi H, Maddison SM. The reduction of dose in paediatric panoramic radiography: the impact of collimator height and programme selection. *Dentomaxillofac Radiol* 2015; **44**: 20140223. doi: <https://doi.org/10.1259/dmfr.20140223>
19. Al-Okshi A, Nilsson M, Petersson A, Wiese M, Lindh C. Using GafChromic film to estimate the effective dose from dental cone beam CT and panoramic radiography. *Dentomaxillofac Radiol* 2013; **42**: 20120343. doi: <https://doi.org/10.1259/dmfr.20120343>
20. Hellén-Halme K, Nilsson M. The effects on absorbed dose distribution in intraoral X-ray imaging when using tube voltages of 60 and 70 kV for bitewing imaging. *J Oral Maxillofac Res* 2013; **4**: e2. doi: <https://doi.org/10.5037/jomr.2013.4302>
21. Ma CM, Coffey CW, DeWerd LA, Liu C, Nath R, Seltzer SM, et al. American Association of Physicists in Medicine AAPM protocol for 40–300 kV x-ray beam dosimetry in radiotherapy and radiobiology. *Med Phys* 2001; **28**: 868. doi: <https://doi.org/10.1118/1.1374247>
22. Cristy M. Active bone marrow distribution as a function of age in humans. *Phys Med Biol* 1981; **26**: 389–400. doi: <https://doi.org/10.1088/0031-9155/26/3/003>
23. ICRP Adult reference computational phantoms. ICRP Publication 110. *Ann ICRP* 2009; **39**: 1–165.
24. ICRP The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP* 2007; **37**: 1–332. doi: <https://doi.org/10.1016/j.icrp.2007.10.003>
25. Rampado O, Garelli E, Ropolo R. Computed tomography dose measurements with radiochromic films and a flatbed scanner. *Med Phys* 2010; **37**: 189–96. doi: <https://doi.org/10.1118/1.3271584>
26. Tomic N, Quintero C, Whiting BR, Aldelaijan S, Bekerat H, Liang L, et al. Characterization of calibration curves and energy dependence GafChromic™ XR-QA2 model based radiochromic film dosimetry system. *Med Phys* 2014; **41**: 62105. doi: <https://doi.org/10.1118/1.4876295>
27. Alqerban A, Willems G, Bernaerts C, Vangastel J, Politis C, Jacobs R. Orthodontic treatment planning for impacted maxillary canines using conventional records versus 3D CBCT. *Eur J Orthod* 2014; **36**: 698–707. doi: <https://doi.org/10.1093/ejo/cjt100>
28. Wriedt S, Jaklin J, Al-Nawas B, Wehrbein H. Impacted upper canines: examination and treatment proposal based on 3D versus 2D diagnosis. *J Orofac Orthop* 2012; **73**: 28–40. doi: <https://doi.org/10.1007/s00056-011-0058-8>
29. Hidalgo Rivas JA, Horner K, Thiruvengkatachari B, Davies J, Theodorakou C. Development of a low-dose protocol for cone beam CT examinations of the anterior maxilla in children. *Br J Radiol* 2015; **88**: 20150559. doi: <https://doi.org/10.1259/bjr.20150559>
30. Rampado O, Bianchi SD, Peruzzo Cornetto A, Rossetti V, Ropolo R. Radiochromic films for dental CT dosimetry: a feasibility study. *Phys Med* 2014; **30**: 18–24. doi: <https://doi.org/10.1016/j.ejmp.2012.06.002>
31. Ludlow JB, Davies-Ludlow LE, Brooks SL. Dosimetry of two extraoral direct digital imaging devices: NewTom cone beam CT and Orthophos Plus DS panoramic unit. *Dentomaxillofac Radiol* 2003; **32**: 229–34. doi: <https://doi.org/10.1259/dmfr/26310390>
32. Mattsson S. Need for individual cancer risk estimates in X-ray and nuclear medicine imaging. *Radiat Prot Dosimetry* 2016; **169**: 11–16. doi: <https://doi.org/10.1093/rpd/ncw034>
33. Brenner DJ. Effective dose: a flawed concept that could and should be replaced. *Br J Radiol* 2008; **81**: 521–3. doi: <https://doi.org/10.1259/bjr/22942198>
34. U.S. Environmental Protection Agency. EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population Report No: EPA Publication 402-R-11-001. 2011.