

# Cone Beam Computed Tomography and Impacted Maxillary Canines

Dose, Optimisation, and Justification

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Randi Lynds Ihlis

Thesis for the degree of Philosophiae Doctor (PhD)  
University of Bergen, Norway  
2022

UNIVERSITY OF BERGEN



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My angels on my shoulder - Don and Marj Lynds

My best friend and partner through time - Johan Ihlis

My little hearts outside my body - Leo and Olivia

I couldn't have done this without any of you,  
thank you all.

“Be brave.” - In loving memory of my grandfather.



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## SCIENTIFIC ENVIRONMENT

The studies comprising this thesis were conducted during 2016 - 2022 under the supervision of Professor Xie-Qi Shi as the main supervisor, and Associate Professor Georgios Tsilingaridis and Dr. Daniel Benchimol as co-supervisors.

The scientific work took place at the Department of Oral Diagnostics and Rehabilitation, Karolinska Institutet, Stockholm, Sweden in collaboration with the Department of Orthodontics and Paediatric dentistry. The scientific element of this doctoral thesis was completed at the Department of Clinical Dentistry, University of Bergen, Bergen, Norway and at multiple institutions nationally in Sweden as part of the Swedish National Clinical Research School program in Odontology, founded by the Swedish Research Council. A doctoral research environment leading to the completion of this thesis was provided by the Centre for Clinical Research, Falun, Sweden.

The imaging data were collected at Karolinska Institutet, Eastman Institutet Folk tandvården, and Huddinge Specialistkliniken, in Stockholm, Sweden.

*“I am among those who think that science has great beauty.”*

*Marie Curie (1867 - 1934)*

## SUMMARY

Impacted maxillary canines are the most common reason for Cone Beam Computed Tomography (CBCT) examinations of the anterior maxilla in children and adolescents today. If impacted canines are missed or diagnosed late, root resorptions may occur on permanent adjacent incisors. In turn, these resorptions may lead to the need for further orthodontic treatment, surgical extractions, and even implants or other prosthetic solutions. Impacted canines are usually discovered in children via clinical examinations in combination with intraoral periapical radiographs and panoramic images. When more diagnostic information is needed, the next step is a CBCT examination. While regulating authorities in radiation protection agree that CBCT should not be used first-hand, there is still no consensus over whether CBCT alters therapy planning amongst clinicians.

The ideal radiographic modality and exposure parameters vary, depending on each individual clinical task. When using ionizing radiation to examine patients, attention must be paid to the balance between the benefit to the patient and clinician contra the radiation risk. This thesis aimed to assess the radiation dose burden to children examined for impacted canines and explore methods of limiting dose exposure by applying optimised low-dose protocols and by limiting CBCT examinations through a justification process performed at the therapeutic thinking level.

The first paper aimed to measure the effective dose using two-dimensional (2D) examinations (panoramic and periapical radiographs) and three-dimensional (3D) CBCT devices. 2D examination doses and CBCT doses from two devices (Promax3D and NewTom 5G) were compared after measuring organ doses on an anthropomorphic child phantom. The dose from CBCT examinations ranged from 15 to 140 times higher than conventional 2D examinations, depending on the CBCT unit and the type of 2D examination.

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The second paper evaluated overall image quality and visibility of anatomic structures on low-dose CBCT scans and the effect of a noise reduction filter for assessment of the anterior maxilla. Multiple CBCT protocols (Promax3D), including four low-dose protocols, were tested on dry skull phantoms to compare overall image quality and visibility of anatomic structures pertinent to impacted canine assessment. Of the low-dose protocols, three provided acceptable diagnostic image quality while reducing the dose by 61% – 77%.

The third paper investigated how CBCT affects the treatment plan of patients with impacted canines, as well as identified possible clinical and 2D imaging markers for the justified CBCT examination at the therapeutic thinking level. To decide whether CBCT was justified for therapy planning, an interdisciplinary therapy-planning group evaluated impacted canine cases and decided treatment alternatives, first without and later in addition to diagnostic information from CBCT examinations. More than half of the CBCT examinations were considered unjustified, and the therapy plan changed in 9.8% of the cases. Variables measured prior to CBCT that predict the need for further CBCT examinations were horizontally positioned canines (OR= 10.9,  $p = 0.013$  when compared to vertically positioned canines), when extraction strategy was involved (OR = 6.7,  $p = 0.006$ ), and buccally positioned canines when compared to palatal (OR = 5.3,  $p = 0.047$ ), central (OR = 25.0,  $p = 0.001$ ), and distal or uncertain positions (OR =7.7,  $p = 0.005$ ).

Even when optimised, CBCT examinations come at the cost of a higher radiation dose than conventional 2D images. Based on the papers comprising this thesis, patient dose burdens can be minimized when assessing impacted maxillary canines in radiosensitive paediatric patient populations by 1) optimising low-dose CBCT protocols and 2) limiting CBCT exposures to cases where additional 3D information is important for therapeutic thinking and planning.



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## NORSK SAMMENDRAG

Retinerte hjørnetenner i overkjeven som er sperret av andre tenner for å vokse ut, er den vanligste grunnen til bruk av Cone Beam Computed Tomography (CBCT) hos barn og unge. Hvis diagnostisering av de retinerte hjørnetenner mangler eller kommer sent, kan rotresorpsjon forekomme på de permanente nabo tennene. Resorpsjonene kan senere føre til behov for kjeveortopedisk behandling, kirurgiske ekstraksjoner og i noen tilfeller implantat eller andre proteseløsninger. Retinerte hjørnetenner oppdages vanligvis hos barn ved klinisk undersøkelse i kombinasjon med intraorale og panorama røntgenbilder. Når mer informasjon er nødvendig for diagnostikk og planlegging, er CBCT-undersøkelse berettiget. På grunn av råd om strålevern er det enighet om at CBCT ikke bør brukes ved førstehånds undersøkelse, men det er fortsatt ingen konsensus om hvorvidt CBCT påvirker terapiplanlegging blant klinikere.

Den ideelle radiografiske modaliteten og eksponering varierer, avhengig av den klinisk situasjonen. Når ioniserende stråling benyttes for å undersøke pasienter, må man være oppmerksom på balansen mellom fordelene for pasienten og klinikeren og risikoen ved stråling. Denne doktorgradsavhandlingen hadde som mål å vurdere belastningen ved strålingsdose for barn der retinerte hjørnetenner ble undersøkt. Avhandlingen ser også på metoder for å begrense doseeksponering ved å bruke protokoller for å optimaliserte en lav dose og begrense CBCT-undersøkelsene.

Første artikkel i avhandlingen hadde som mål å se effektiv dose ved å sammenligne todimensjonale (2D) undersøkelser (panorama og periapikale røntgenbilder) og tredimensjonale (3D) CBCT. Dosen fra 2D-undersøkelse og CBC fra to enheter (Promax3D og NewTom 5G) ble sammenlignet etter måling av doser på et antropomorft barnefantom. Dosen fra CBCT-undersøkelsen var fra 15 til 140 ganger høyere enn for de konvensjonelle 2D-undersøkelsene, avhengig av CBCT-enhet og type 2D-undersøkelse.

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Andre artikkel evaluerte bildekvalitet og synlighet av anatomiske strukturer på lavdose CBCT-skanning og effekten av et støyreduksjonsfilter for vurdering av overkjevens front. Flere CBCT-protokoller (Promax3D), blant annet fire lavdoseprotokoller, ble testet på skallefantomer for å sammenligne bildekvalitet og synlighet av anatomiske strukturer som er relevante for vurdering av retinerte hjørnetenner. Tre av lavdoseprotokollene gav akseptabel diagnostisk bildekvalitet, selv om dosen ble redusert med 61 % – 77 %.

I tredje artikkel ble det undersøkt hvordan CBCT påvirker behandlingsplanen til pasienter med retinerte hjørnetenner, samt mulige kliniske og 2D-bilde markører for planlagt CBCT-bruk. For å avgjøre om CBCT var berettiget for planlegging av behandling, evaluerte og planlagt en tverrfaglig gruppe 89 kasus med retinerte hjørnetenner. Mer enn halvparten av CBCT-undersøkelsene ble vurdert som uberettiget. Planlagt behandling ble endret i 9,8 % av tilfellene. Variable målt for CBCT som predikerte behovet for ytterligere CBCT, var horisontalt plasserte hjørnetenner, strategi for ekstraksjon på permanente tenner, og bukkalt posisjonerte hjørnetenner.

Denne avhandlingen viser at, CBCT medfører høyere effektiv dose for pasienter sammenlignet med konvensjonell 2D røntgenbilder. Dosene pasienter får ved undersøkelse av retinerte hjørnetenner kan minimeres ved å 1) optimalisere protokoller for lavdose CBCT og 2) begrense bruk av CBCT til tilfeller der ytterligere 3D-informasjon er viktig for videre terapeutisk behandling.

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## ABBREVIATIONS

3D	Three-dimensional
2D	Two-dimensional
ALADA	As low as diagnostically acceptable
ALARA	As low as reasonably achievable
ALADAIP	As low as diagnostically acceptable, indication oriented, and patient-specific
CBCT	Cone beam computed tomography
CNR	Contrast-to-noise ratio
CT	Computed tomography
DAP	Dose-area product
FOV	Field of view. Defined as diameter times height for CBCT
Gy	Gray. J / kg Unit for kerma and for absorbed dose
ICRP	International Commission on Radiological Protection
kV	Kilovoltage, tube voltage
mAs	Milliamperere-seconds, tube current-exposure time product
SEDENTEXCT	Safety and Efficacy of a New and Emerging Dental X-ray Modality
SNR	Signal-to-noise ratio
Sv	Sievert
TLD	Thermoluminescent dosimeter
AINO filter	Adaptive Image Noise Optimiser (Planmeca)
ULD	Ultra low-dose

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## LIST OF PUBLICATIONS

This thesis is based on the following three papers, which will be referred to by their Roman numerals I – III:

- I      Kadesjö N, **Lynds R**, Nilsson M, Shi XQ.  
Radiation dose from X-ray examinations of impacted canines: cone beam CT vs two-dimensional imaging. *Dentomaxillofac Radiol.* 2018;47(3):20170305.
- II     **Ihlis RL**, Kadesjö N, Tsilingaridis G, Benchimol D, Shi XQ.  
Image quality assessment of low-dose protocols in cone beam computed tomography of the anterior maxilla. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 2022 Apr;133(4):483-491.
- III    **Ihlis RL**, Giovanos C, Liao H, Ring I, Malmgren O, Tsilingaridis G, Benchimol D, Shi XQ.  
Cone beam computed tomography indications for interdisciplinary therapy planning of impacted canines. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 10.1016/j.oooo.2022.06.013; Epub 2022 Jul.

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# 1 INTRODUCTION

## 1.1 Impacted maxillary canines

*" No tooth is more interesting from a developmental point of view than the upper cuspid. Of all the teeth it has the longest period of development, the deepest area of development, and the most devious course to travel from its point of origin to full occlusion. " - Dewel, 1949<sup>1</sup>*

In approximately 1 - 5.2% of the population worldwide, varying between ethnicities, normal eruption of the maxillary canine does not occur and the tooth is then said to be impacted.<sup>2-4</sup> Various terms and definitions are currently used in the literature when describing impacted canines. These terms include canine displacement, delayed eruption, primary retention, ectopic eruption, disturbed eruption, submerged teeth, and more. According to a relatively recent systematic review, there was no consensus over the classification system of displaced or impacted teeth.<sup>5</sup> For the sake of clarity, in this thesis, a maxillary canine is considered impacted when the tooth is embedded in the alveolus with its eruption prevented and delayed.<sup>6-8</sup>

Maxillary canines are the most frequently impacted tooth after the third molar, occurring twice as often in females when compared to males.<sup>9, 10</sup> Normally, permanent maxillary canines erupt between nine to 13 years of age.<sup>11</sup> Early diagnosis and proper treatment are essential for improving the canine's prognosis in reaching a correct position in the dental arch.<sup>12, 13</sup> Diagnosis of impacted canines are based on clinical palpation and radiographic examinations, including periapical intraoral, occlusal and panoramic radiographs. A limitation of these methods is that maxillary canines often overlap the incisor's root, making possible resorption difficult to assess in the bucco-palatal direction.<sup>14, 15</sup>



When left untreated, impacted canines are seen to cause root resorptions of adjacent teeth 26 - 67% of the time.<sup>16-18</sup> Inadequate management of impacted canines or canine-induced resorptions result in the need for further expensive treatments, including extraction, orthodontic treatment, reconstructions or even implants.<sup>19</sup> Much attention is given to the importance of prompt discovery and treatment of these teeth in paediatric dentistry today.

## **1.2 Conventional two-dimensional radiographic assessment**

Up to 10% of children require a radiographic examination to locate permanent maxillary canines during development.<sup>11, 20</sup> Conventional methods consist of varying combinations of intraoral and extraoral two-dimensional (2D) images (Figure 1).

In Sweden, intraoral radiography is the most commonly used imaging modality in dentistry, comprised of periapical and bitewing projections. Since these images are 2D representations of three-dimensional (3D) objects, localising a specific anatomic structure in relation to other structures in the bucco-palatal plane is difficult or impossible when only a single image is available. A maxillary occlusal projection may also be used, although this method is not common in Sweden. To localise structures in a 3D perspective, two intraoral images with different projections are compared to each other according to Clark's rule, otherwise known as the tube-shift method or the parallax technique. (Figure 1).<sup>21</sup> There are additional limitations of intraoral digital sensor imaging due to the size of the sensor: important information may not fit on the area of the detector, and some patients experience intraoral digital sensors as bulky and uncomfortable.

Extraoral modalities, including panoramic and lateral cephalograms are also often used for canine assessment, many times in combination with intraoral images. Patients with impacted canines often need to be radiographically assessed preliminarily for orthodontic treatment, therefore panorama and cephalometric images are usually readily available and contribute to the localisation of impacted canines and their relation to surrounding structures.

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The most common extraoral imaging modality is the panoramic radiograph, which provides a single image overview of the dentomaxillofacial region. A panoramic image is produced by placing the patient between the radiation source and the attached sensor. As the X-ray tube head moves around one side of the patient, the image receptor assembly moves towards the opposite side.<sup>22</sup>

Due to the tomographic nature of the panoramic technique, patient-positioning and head alignment are essential to minimise size and shape distortions and obtain reliable diagnostic information, especially in the anterior region, due to the narrow focal trough of panoramic images and the superimposition of the cervical spinal column. While the focal trough of the panorama image is mathematically formed as a hypothetical dental arch, this form doesn't always correlate well with variations in patient anatomy. The distance and position of the impacted canine in relation to this imprecise focal trough affects the resulting appearance of canines in panoramic radiographs, and canine inclination and position may be falsely depicted in these images.<sup>23, 24</sup>

The main drawback of 2D imaging techniques is that when 3D structures are visualised in 2D, a loss of depth information occurs. This results in a summation image, where all the structures that the X-ray beam passes through appear on the image as overlapping one another or superimposed. This may contribute to clinicians missing diagnostic information, such as root resorptions or other abnormalities. While 2D images should be used as the first step in assessing impacted canines, only approximately 50% of resorptions on the buccal or palatal surfaces of incisors roots are detected with 2D techniques.<sup>19</sup>



**Fig. 1.** Panoramic and intraoral radiographs (Patient case taken from Paper III case material). The periapical intraoral radiographs show both the left and right maxillary canine palatal to the lateral incisors by utilising the parallax technique.

When conventional 2D radiographic examinations cannot provide enough diagnostic information, the current European guidelines recommend supplementing these images with cone beam computed tomography (CBCT).<sup>25</sup>

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## **1.3 Cone beam computed tomography**

### **1.3.1 Overview**

CBCT is a volumetric imaging modality that has many dental and maxillofacial applications. CBCT devices utilise a divergent (cone-shaped) source of ionising radiation and a flat-panel detector situated on the opposite side of a gantry that rotates around the patient's head. During one single rotation scan, multiple sequential 2D images within the pre-determined field of view (FOV) are acquired.<sup>26</sup>

CBCT volumes cause no discomfort to the patient during image acquisition and are quick to obtain, with a scan taking approximately 5 – 40 seconds to complete.<sup>27</sup> Once acquired, these projection images can be quickly reconstructed as merged images in the sagittal, coronal, and axial planes, resulting in 3D volumes with high spatial definition when compared to conventional multi-slice computed tomography (CT). The contrast resolution of CBCT however, is inferior to conventional multi-slice CT and thus unsuitable for imaging low-contrast objects, such as soft tissue. Many studies have reported that CBCT images are accurate and reliable in detecting anatomical and pathological changes in hard tissue, making CBCT valuable in dentistry.<sup>28, 29</sup>

CBCT has been used in dentistry since 1998, and the application of CBCT technology has since increased rapidly. Currently, CBCT is used in many dental clinics, worldwide. The most common reason for obtaining a CBCT in the paediatric patient population is to assess impacted maxillary canines.<sup>30, 31</sup> While CBCT is popular and useful, special attention should be paid to the higher radiation burden CBCT entails for this young patient group.

### **1.3.2 Technical parameters affecting dose**

As with all radiographic modalities in practice, understanding technical parameters of CBCT devices, along with their accompanying scanning protocol variables, is essential for dose optimisation. Many different unit manufacturers exist - each with their own different protocols, parameters, solutions, software with market secrets - adding to the

complexity of understanding and comparing CBCT equipment. However, a basic understanding of the parameters that all CBCT units share is useful when considering dose-reduction strategies in general.

### *Exposure parameters*

Beam quantity refers to the number of photons in an X-ray beam, mostly determined by tube current (mA), exposure times, tube voltage (kV), and tube filtration; whereas beam quality refers to the shape of the energy spectrum effected by the tube potential and the applied filtration.

Some devices allow exposure time and mA to be adjusted separately, but their combined product, the tube current-exposure time product (mAs) is always directly proportional to absorbed dose. The mAs determines the quantity of X-ray photons in the beam. Increasing either exposure time or tube current results in an increased dose. The quality of X-ray beam energy and quantity of photons in the beam is influenced by tube voltage, expressed as kilovolts (kV). The effect of kV on radiation dose is not linear, and is more complex than mAs.<sup>32</sup>

Tube filtration, usually by means of aluminium or copper filtration, filters low energy X-ray photons from the beam. Low energy photons are more likely to be absorbed by the patient and interact with biological tissue, resulting in the patient receiving a high absorbed dose that doesn't contribute to the image. Increased filtration has been shown to reduce absorbed dose while raising the mean energy of the spectrum.<sup>33, 34</sup>

### *Voxels*

Voxels are 3D pixels and are the smallest 3D element of a CBCT volume. Their size can range from 75  $\mu\text{m}$  – 600  $\mu\text{m}$ .<sup>35</sup> While small voxels increase the theoretical spatial resolution allowing finer details to be displayed, an increase in radiation dose is needed to maintain the same signal-to-noise (SNR) ratio.<sup>36</sup> The noise level in an image is associated with the number of photons that reach the detector. As voxels decrease in size, the number of photons in each voxel also decreases, resulting in increased image

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noise. Therefore, to keep the same level of SNR, a sharp image with a higher spatial resolution is obtained at the cost of a higher radiation dose.

### *Field of View*

FOV refers to the anatomical area of the patient that is irradiated and shown in the data volume. Depending on the diagnostic task, the FOV can be adjusted to include only the area of interest. Most CBCT devices offer a limited range of fixed FOVs, however, more recent models allow operators to freely adjust the collimation to their individual preference in the x, y, and z-direction.<sup>37</sup> The FOV is one of the main determining factors of effective dose, and decreasing the FOV size leads to lower radiation doses when keeping other exposure parameters the same.<sup>38</sup>

### *Exposure frames*

During CBCT acquisition, rotation trajectory arcs vary between 180° - 360° and the beam exposure can either be constant or pulsed. Decreasing the trajectory arc or pulsing exposures decreases exposure time and results in fewer exposure frames, which reduces the total radiation dose to the patient. However, if insufficient frames are obtained, there is an increased risk of producing image artefacts.

### *Detector properties*

What makes CBCT unique is the Cesium Iodide (CsI) scintillator in the flat-panel detector, which provides a high pixel density with minimal resolution reduction, allowing for high sensitivity in high-resolution images. This allows CBCT to produce images with better spatial resolution than a medical CT, albeit with a trade-off of worse contrast resolution. The smaller voxel size of CBCT also contributes to noisier images unless a higher radiation dose is used as compensation. As a scintillator, CsI is relatively slow, which means that the rotation time for CBCT imaging needs to be slower to prevent detector afterglow that may be present for a certain time after the X-ray excitation ceases. The slower rotation time of CBCT increases the risk of motion artefacts, which appear as blurred images.<sup>39</sup> This presents a disadvantage of CBCT

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examination on younger patients, who often have difficulties remaining still under the duration of the scan.<sup>40</sup>

### **1.3.3 Image quality assessment**

Image quality describes the precision and accuracy of an image in relation to the visualisation of structures that are important for the image's intended diagnostic task.<sup>41</sup>

Lowering doses can result in a reduced SNR and thus inferior image quality, however noise within a certain range may still be acceptable when the noise doesn't affect the diagnostic effectiveness of a subjectively inferior image.<sup>42</sup>

Image quality can be assessed objectively by comparing diagnostic outcomes or subjectively by performing relevant diagnostic tasks and involving observers.

#### *Objective Image Quality*

Image quality can be objectively quantified by employing test phantoms and mathematical algorithms. Objective measurements allow quantification of physical parameters of image systems which affect image quality in terms of sharpness/spatial resolution, contrast transfer/contrast resolution and the noise levels/ SNR.<sup>43</sup>

Small structures and fine details require high spatial resolution to be seen. High spatial resolution, however, comes at the cost of a higher dose. Lowering the dose by means of lowering mAs or kV results in fewer X-ray photons in the beam, which causes increased noise in the image. Noise in images gives a grainy appearance. SNR describes the true signal representing objects in the image in relation to the noise of the image. The lower the dose, the more the noise, or image graininess, increases. If a structure has a similar contrast to neighbouring structures, image noise can make the visibility of the structure difficult or impossible to assess.

#### *Subjective Image Quality*

The ultimate goal of a diagnostic imaging system is to provide optimal image quality so that the images can be used by clinicians for various diagnostic purposes.

Therefore, new imaging systems and technologies must also be tested subjectively by

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performing relevant diagnostic tasks involving professionals. Images with diagnostically acceptable image quality reduce the need for repeat exposures, resulting in a lower overall dose for patients. The concept of what a diagnostically acceptable image is, though, is complex. Objective image quality is important, but insufficient as a single measure of the adequacy of image quality. While objective image quality testing considers the physical properties and performance of an imaging system, neither observers nor a specific diagnostic task is involved in the assessment. Certain structures are important to visualise for a therapy plan to be optimal, while other structures are less important, depending on the clinical task. Therefore, the requirement on what entails an acceptable image quality is dependent on what the diagnostic task in individual situations calls for, as well as the interpreter of the image's clinical experience, visual acuity, and subjective preferences.

Efforts have been made to develop low-dose CBCT by applying more sensitive image receptors and by sophisticated image processing algorithms at the expense of reduced image quality. Evaluating image quality is complicated and should not be limited to evaluating the physical properties of a system alone.<sup>44</sup> There are currently few studies on how varying patient doses correlate with subjective image quality relating to specific clinical tasks, leaving a great need to evaluate image quality in relation to a specific diagnostic task before it may be recommended for clinical use.

## **1.4 Dosimetry**

### **1.4.1 Dosimetric quantities**

#### *Air kerma and dose-area product*

An easy way to quantify the radiation delivered from a radiographic device is by means of a dose index. The dose index used for intraoral, panoramic and CBCT modalities is the dose-area product (DAP).

For practical reasons, DAP is a valuable index recommended for comparing doses exposed on the same area using the same energy level. To calculate the DAP, the mean



air kerma (Gy) within the beam field is multiplied with the beam area ( $\text{cm}^2$ ). The result is expressed in milligray per centimetre squared ( $\text{mGycm}^2$ ) and provides an indication of the dose the patient receives. DAP is measured by intercepting the entire beam field between the tube and the patient with a transmission ionising chamber placed outside the X-ray tube/collimator. DAP is a measure of the entry dose, and not a measure of X-ray photons interacting with tissues and organs.

#### *Absorbed dose*

The absorbed dose, expressed in the unit of Gray (Gy), is a measurable physical quantity that describes the amount of ionising radiation deposited into a unit of mass. Since it varies with the type of radiation and matter absorbing the energy, the absorbed dose does not represent the risk of radiation harm.

#### *Equivalent dose*

Equivalent dose ( $H_T$ ) is expressed in units of Sievert (Sv).  $H_T$  is calculated for individual organs or tissues and accounts for the effectiveness of different types of radiation. To quantify the  $H_T$ , the absorbed dose of an organ is multiplied with the weighting factor for the radiation type. This results in a dose measurement that takes into consideration the biological effect of different types of radiation on tissues and organs.

#### *Effective dose*

The effective dose, also expressed in units of Sv, is calculated for the entire body by multiplying the  $H_T$  of separate organs and tissues with a tissue weighting factor ( $W_T$ ) that adjusts for differences in organ dose sensitivity and relative stochastic risk levels, such as the risk of cancer formation and genetic effects. The sum of effective doses from each tissue and organ results in the total effective dose.

The ICRP has derived different weighting factors, with the most recent list published in 2007 (Table 1).  $W_T$  is defined at a population level, meaning that effective dose measurements cannot be used to quantify individual risks or risks in specific

populations, for example, specific age groups.

**Table 1.** Effective dose tissue weighting factors of the ICRP 2007

Tissue	$W_T$	$\Sigma W_T$
Red bone-marrow, colon, lung, stomach, breast, remaining tissues*	0.12	0.72
Gonads	0.08	0.08
Urinary bladder, oesophagus, liver, thyroid	0.04	0.16
Endosteum (bone surface), brain, salivary glands, skin	0.01	0.04
	<b>Total:</b>	<b>1.00</b>

\*Remaining tissues: Adrenals, extrathoracic airways, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀)

The ICRP considers effective dose as a useful tool when comparing radiation burden results from different modalities.<sup>45</sup>

#### 1.4.2 Radiation risk assessment

Effective dose is used to assess the risk of cancer formation and genetic effects. Four different methods are available for measuring absorbed dose: 1) The thermoluminescent dosimeter (TLD) technique, 2) GafChromic films, 3) the Metal-oxide-semiconductor field effect transistor (MOSFET) dosimeters technique, and 4) Monte Carlo dosimetry. The two dose measurement methods used in this thesis were the TLD method and GafChromic film.

##### *Thermoluminescent dosimeters*

The most common method for measuring absorbed dose is the TLD technique.<sup>38, 46-48</sup> Traditionally, effective dose in dentomaxillofacial radiology has been measured by using TLDs placed in anthropomorphic head and neck phantoms to measure organ doses.<sup>34, 49-51</sup> Phantoms contain real or bone-equivalent material and are separated into multiple slices. Each slice has small cavities that have been drilled to allow TLD placement in the regions of radiosensitive organs. When TLDs are exposed to ionising radiation, electrons are freed and positively charged atoms appear.

Repeat exposures are often needed to increase the reliability of TLD dose readings. The TLDs are removed from the phantom and heated, which causes energy to be released as a measurable light intensity. Once the light intensity is measured and adjusted to the number of exposures as well as the exposed organ, the effective dose of this organ is obtained.

The TLD method works well for measuring doses in large X-ray fields where there is a somewhat homogenous dose distribution. However, sharp dose gradients occur when using panoramic X-ray geometry, which is problematic for TLD measurements. The TLD detectors might chance upon a high dose area or almost miss the dose entirely. Therefore, organ doses can't be determined from point measurements, such as TLDs. Additionally, this method is time-consuming, as each individual dosimeter must be read, annealed, and repositioned for dose readings.

### *GafChromic film*

Instead of using dosimeter techniques, GafChromic films can be used in dose studies.<sup>52, 53</sup> GafChromic film records the absorbed dose distribution by being first placed between the different levels, or slices, of a phantom before exposure, and then after exposure, the pixel values are converted to absorbed dose distributions.<sup>52</sup> GafChromic film covers the entire cross-section of the phantom and any desired measurement area can be defined.

Intraoral X-rays use a very localised dose which can be challenging for dose measurements. Additionally, the sensor absorbs almost all incoming dose in a clinical setting, but in an experimental setting, it isn't possible to place a sensor inside the phantom. With film, we can easily correct the signal behind the sensor by correcting the position on the dose map as well as correcting the signal behind the sensor.

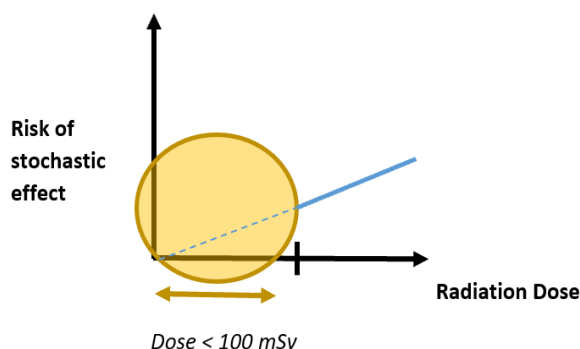
Compared with TLDs, GafChromic film is easy to prepare and much less labour intensive and time consuming. However, both techniques have an inherent risk when scattered radiation is present. If there is no TLD or film precisely where the scattered radiation is distributed, the reading will be missed. Film, however, is better for

catching scattered radiation than TLDs are. The primary drawback for film is the smaller dynamic range, of 1 mGy to 200 mGy, which is much lower than TLD. Therefore, it may not be possible to both measure the absorbed dose in the primary field and in low-dose areas at the same time.

## 1.5 Radiation protection and the paediatric patient

### 1.5.1 Radiation protection

Radiographic diagnostic imaging techniques use ionising radiation with enough energy to potentially damage cellular DNA, which may then potentially lead to radiation-induced stochastic effects, such as cancer development or hereditary effects, appearing later in life. Currently, radiation protection guidelines are based on the linear no-threshold (LNT) model, which suggests there is no lower-limit cut-off threshold below which exposure doses can be considered risk-free. The LNT model implies that the additional risk of stochastic effects is approximately proportional to dose, even at low levels of less than 100 mSv, and that the sum of multiple low dose exposures is as likely to have the same detrimental effect as a single larger exposure. (Figure 2) Some schools of thought propose that risks may be higher or lower than the LNT model suggests, and that doses lower than a theoretical threshold may have biologically protective effects.<sup>54, 55</sup>



**Fig. 2.** The Linear non-threshold model, with emphasis on the highlighted uncertainties at dose levels lower than 100 mSv.

Despite uncertainties at lower dose levels, assessment of the risks of using ionising radiation for diagnostic imaging is an important public health issue. Radiographs taken as a part of dental care are among the most common source of medical exposures globally, and while these doses are often small, due to the high volume of exposures they cannot be disregarded.<sup>56</sup> This is especially true for children and adolescents undergoing orthodontic treatment, as their risk is increased due to repeated X-ray exposures as a part of their orthodontic evaluations.<sup>57</sup>

Radiation protection policies, regulations, and guidelines are largely based on recommendations from the International Committee of Radiation Protection (ICRP).<sup>58</sup> According to ICRP, all radiographic examinations of patients should be justified and optimised. To mediate this, the ICRP introduced a fundamental principle in radiation protection, commonly known as the “ALARA” principle, which is an acronym for “as low as reasonably achievable”. To comply with the ALARA principle, radiographs should only be taken if they are beneficial for the individual patient’s therapy outcome when compared to the potential risk of ionizing radiation, even when the dose is low. In practice, this can only be achieved after considering individual indications.

As there is no currently known threshold for a safe low dose, the ICRP and other regulating authorities stress the importance of continual dose optimisation, according to a modified “ALARA” principle, the “ALADA” principle, which stands for “as low as diagnostically achievable.” To comply with the ALADA principle, the dose level of radiographs should be as low as possible while at the same time still providing enough diagnostic information to maintain a clinically useful image.

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What justification and optimisation mean in practice is that prior to exposing a patient with ionising radiation, the clinician must be clear about:

- what clinical question needs to be answered and whether an X-ray examination is needed
- when an X-ray examination is indicated, which modality should be utilised considering the benefit-risk assessment. This requires knowledge of indications for the available modalities, their advantages, and their shortcomings.
- when the X-ray modality is determined, the exposure protocol should be defined on an individual basis, and
- how the examination is carried out practically.

Rapid developments in the field of radiology and technology require clinicians to continually evaluate work methods and procedures to remain up to date.

### **1.5.2 Radiation risk and the paediatric patient**

Scientific knowledge about the risks of ionising radiation is especially important for children, since children are more radiosensitive than adults. This is due to their bodies containing more water than adults, as well as a higher cell proliferation rate since they are growing.<sup>59</sup> The estimated risk for cancer formation is at least three times higher for children when compared to adults.<sup>25, 60</sup> Studies supporting the plausibility of the LNT model have sparked increased concerns over the potential association between radiation exposure in childhood and cancer, showing evidence of a link between exposure to radiation from medical CT and cancer risk in children.<sup>61-63</sup> Since children have a longer expected lifetime when compared to adults, there is a larger window of opportunity for stochastic effects to manifest.

The DIMITRA group, which stands for Dentomaxillofacial paediatric imaging: an investigation toward low-dose radiation induced risks, have combined the two main radiation protection concepts of justification (indications evaluated on an individual basis) and optimisation (ALARA and ALADA) by introducing the ALADAIP

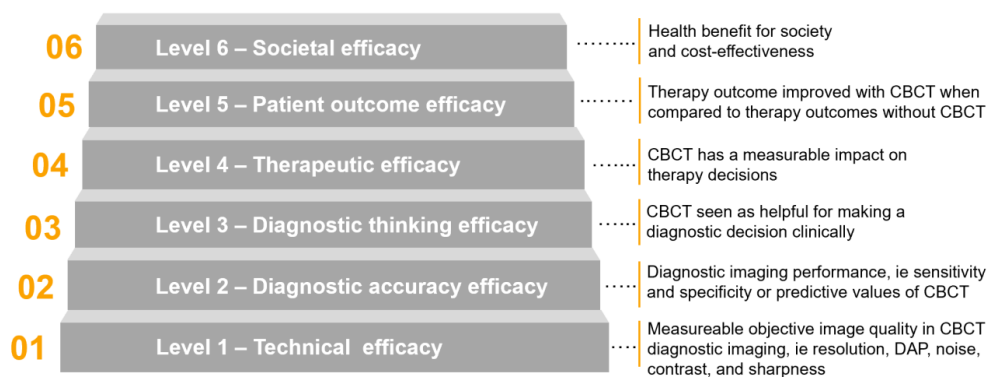
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principle.<sup>31, 64, 65</sup> This principle recommends the use of exposure doses that are “as low as diagnostically acceptable, indication oriented, and patient-specific.” The ALADIP principle highlights the importance of maintaining a balance between obtaining diagnostically acceptable images for the individual clinical task at hand and simultaneously choosing imaging protocols with the lowest dose needed to achieve acceptable image quality.

The SEDENTEXCT consortium, which provides scientific-based evidence regarding radiation protection, reported in 2012 that an intraoral radiograph has an effective dose of  $<1.5 \mu\text{Sv}$  and a panoramic image between  $2.7 \mu\text{Sv} - 24.3 \mu\text{Sv}$ .<sup>25</sup> In the same report, the effective dose range for dento-alveolar CBCT scans measured on a 10 year-old phantom and an adolescent phantom were considerably higher, ranging from  $16 - 214 \mu\text{Sv}$  and  $18 - 70 \mu\text{Sv}$ , respectively. Based on adult phantom studies, the SEDENTEXCT consortium reported that the effective dose for most CBCT units are lower than that of medical CT, however very few studies have looked at effective dose from CBCT units on children.<sup>66</sup> Studies on effective dose determined in adults may not be representative or appropriate for calculating the radiation risk in children. As effective dose is calculated at a population level, different age stratifications and even gender differences are not accounted for in effective dose risk assessments.<sup>45, 56</sup> There is evidence that the radiation burden increases the lower the age of exposure. For example, a dose study from 2012 suggests that even when using the same imaging protocols, a 10-year-old receives a 30% higher effective dose from a dental CBCT examination than an adolescent would, meaning that at the same effective dose exposure level, the stochastic cancer risk is three times higher in children who are approximately 10 years old when compared to adults at 30 years old.<sup>50</sup>

## 1.6 Efficacy of diagnostic imaging

Many factors contribute to which radiographic modality is chosen to assess a range of diagnostic tasks. To conceptualise different aspects that are important for understanding a modality's utility, Fryback and Thornbury's model illustrating six hierarchical levels in diagnostic efficacy is commonly referred to.<sup>67</sup> This model, as seen in Figure 3, provides a framework for understanding how current radiographic methods should be assessed when specifically considering impacted maxillary canines.



**Fig. 3.** CBCT efficacy ladder. This figure is modified from Fryback and Thornbury, 1991.<sup>67</sup>

When clinicians are presented with a clinical task, they are required to choose and utilise the diagnostic modality that has been scientifically shown to be the best available for helping to achieve an optimal treatment outcome. Concerning impacted maxillary canines, the evidence-based selection criteria for CBCT imaging is sparse, and mostly limited to lower-level studies on the efficacy ladder. These lower-level studies look at the objective image quality of diagnostic imaging and the performance of images on images of phantoms or patients.

The reason for a lack of evidence at the higher levels of efficacy is primarily due to the difficulty/feasibility of executing higher level studies. While efficacy of diagnostic imaging on the lower levels is important for enabling efficacy at higher levels, good



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efficacy at the lower levels does not guarantee efficacy at the higher levels. Choosing an appropriate modality should not be limited to technical aspects or diagnostic accuracy either. Currently, this is a problem that clinicians are facing daily. An understanding of how all levels of efficacy pertain to diagnostic modalities of impacted maxillary canines is important, but difficult to accomplish and much is still not known.

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## 1.7 Rationale for this thesis

The fundamental purpose of radiographic imaging is to improve patient care. Radiographs are commonly used to ensure an accurate diagnosis. A disadvantage to radiographic imaging is the unavoidable radiation exposure to the patient. The benefit of using ionising radiation for diagnostic purposes should therefore be clear and assessed in relation to radiation risk. The rationale for this thesis is to minimise the radiation risk by means of justified and optimised use of CBCT on patients with impacted maxillary canines.

This thesis sheds a new light on CBCT assessment of impacted maxillary canines with an emphasis on radiation protection in adolescents. Our work was planned in consideration of the knowledge gaps expressed by the current European guidelines established by the SEDENTEXCT project.<sup>25</sup> Currently, there is a lack of evidence needed to develop clear criteria for correctly targeting the group of patients with impacted maxillary canines in which CBCT examinations are justified.

The image quality needed for the relevant clinical task directly influences the selection of imaging modality as well as the radiation dose level of employed examination protocols. Continual research in image optimisation is greatly needed to create a foundation for further clinical studies. However, dose optimisation protocols should be first tested *in vitro* before used on patients.

## **2 OBJECTIVE**

### **2.1 General aim**

The general aim of this thesis was to analyse the clinical benefit contra radiation risk of CBCT examinations on patients with impacted maxillary canines.

The goal was to better understand

1. the dose burden of CBCT in comparison to conventional radiological modalities for examination of impacted canines.
2. the possibility with optimisation by verifying the low-dose protocols.
3. the impact of CBCT on therapy planning of impacted canines and whether clinical situations could be identified for CBCT justification.

The results can thus contribute to the body of scientific knowledge on CBCT assessment and management of impacted maxillary canines in paediatric patients.

### **2.2 Specific aims**

#### *Paper I*

To compare the radiation dose to children examined for impacted canines, using 2D examinations (panoramic and periapical radiographs) and CBCT.

#### *Paper II*

To evaluate overall image quality and visibility of anatomic structures on low-dose CBCT scans and the effect of a noise reduction filter for assessment of the anterior maxilla.

#### *Paper III*

To investigate how CBCT affects the treatment plan of patients with impacted canines, and to identify possible clinical and 2D imaging markers for the justified CBCT examination at the therapeutic thinking level.

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## **3 HYPOTHESIS**

### **3.1 General Hypothesis**

The general hypothesis of this thesis is that while maintaining an acceptable level of diagnostic information, the radiation dose of CBCT examinations may be reduced by justified selection and optimised application of CBCT.

### **3.2 Specific Hypotheses**

#### *Paper I*

The radiation burden differs considerably between 3D and 2D radiographic examinations, with 3D having a much higher dose burden.

#### *Paper II*

Ultra-low-dose protocols, with up to a 77% lower dose than the standard protocol, may provide diagnostically acceptable image quality for impacted maxillary canine assessment in certain clinical situations. A noise-reduction filter may have a positive effect on image quality.

#### *Paper III*


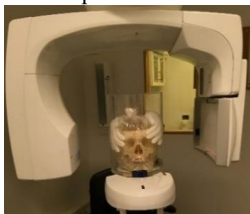
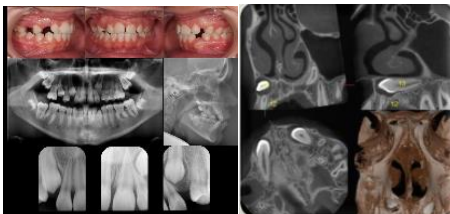
The majority of the cases will have the same therapy plan after additional information from CBCT examinations. The number of CBCT examinations may be minimized by justifying CBCT necessity based on the therapeutic thinking level.

## 4 MATERIAL AND METHODS

### 4.1 Overview

This thesis is based on three papers (Table 2). *Paper I* was a pre-clinical dosimetric study on a paediatric 10-year-old anthropomorphic phantom, used to calculate effective doses from digital intraoral, panoramic, and CBCT images. *Paper II* was an in vitro study using dry skull phantoms to assess subjective image quality and structure visibility in low-dose CBCT protocols intended for impacted canine assessment. *Paper III* was an observational study performed by an interdisciplinary expert panel based on a retrospective cohort.

**Table 2.** Overview of the three studies in the thesis

	<b><i>Paper I</i></b> <b>Dosimetry</b>	<b><i>Paper II</i></b> <b>Optimisation</b>	<b><i>Paper III</i></b> <b>Indication</b>
<b>Design</b>	Observational Phantom Study  1 ATOM-706-C phantom 	Observational In Vitro Study  8 human dry skull phantoms 	Retrospective Observational Cohort Study (89 cases, 132 impacted canines)  2D vs 3D 
<b>Applied radiographic modalities</b>	CBCT Panorama Intraoral	CBCT	CBCT Panorama Intraoral Cephalogram
<b>Applied Methods</b>	Dose measurements -TLD -GafChromic Film	5 observers Analysis of -6 dose protocols -application of a noise reduction algorithm	Interdisciplinary therapy planning: 2D vs 3D
<b>Tested characteristics of examinations</b>	Effective dose level	Optimisation of CBCT	Justification of CBCT

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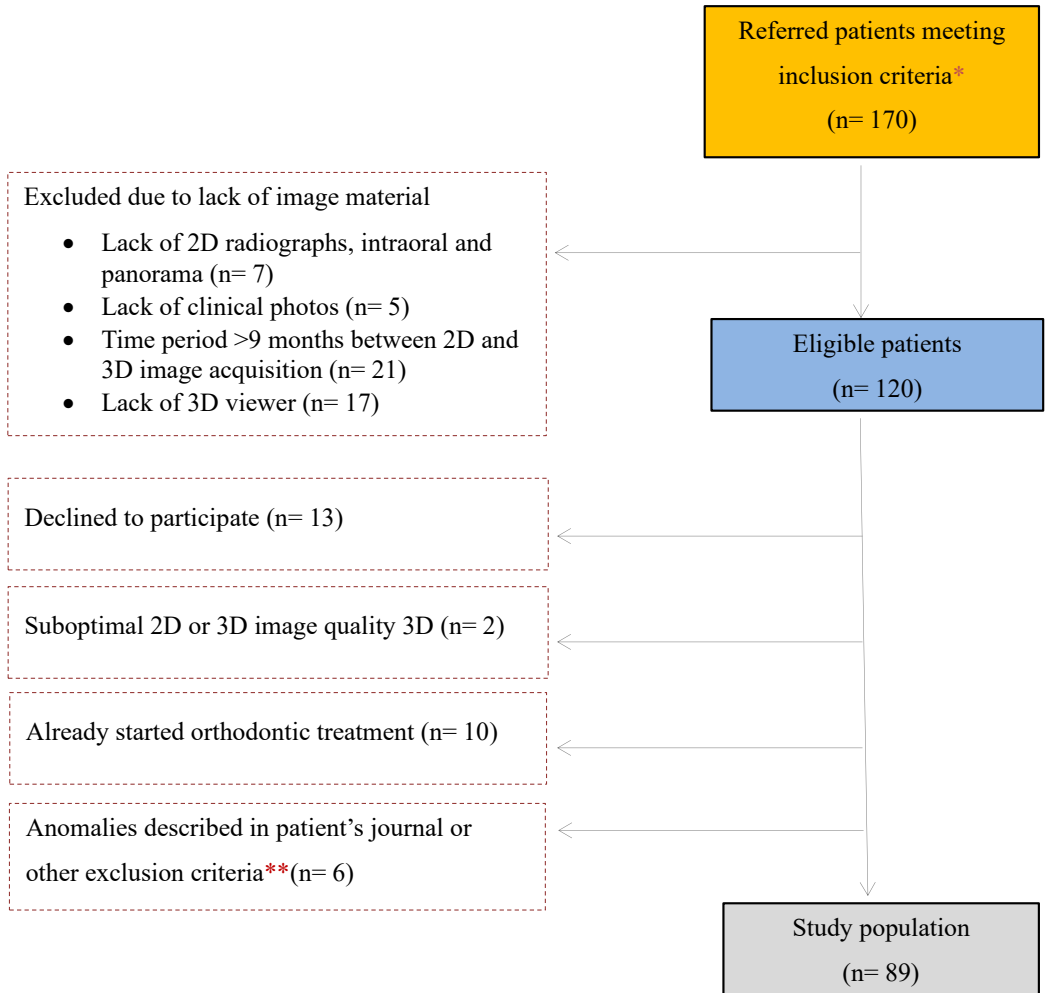
### *Phantoms*

The phantom used for *Paper I* was an anthropomorphic phantom representing a 10-year-old, ATOM-706-C (CIRS, Norfolk, USA), made with tissue-equivalent plastic. This phantom consists of 25 mm thick slices, each containing a grid of pre-drilled holes that are spaced 1.5 cm apart for placement of TLDs. Compared with adult phantoms, this child phantom is smaller, shaped differently, and has a 3% lower electron density of surrogate bone material. *Paper II* was an vitro experiment performed on phantoms constructed using human dry skull specimens and simulated soft tissue, according to Liljeholm et al.<sup>68</sup>

### *Study sample*

*Paper III* is based on a retrospective cohort of patients comprising 89 cases. The cases had CBCT examinations performed for assessing maxillary impacted canines, presenting as either unilateral or bilateral impaction. Cases were collected consecutively from three specialist clinics in the region of Stockholm, Sweden during 2014-2019. The inclusion and exclusion process is illustrated in Figure 4.

In total, 89 patient cases (55 females, 34 males; age range 10.0 – 18.9 years; mean age  $13.3 \pm 1.8$  years) with 132 impacted maxillary canines, were included in *Paper III*.



**Fig. 4.** Study Sample Flowchart

\* Inclusion criteria: CBCT examinations taken because of maxillary canine impaction, maximum age of 19 years, clinical photos or models available, a panoramic image taken within 9 months from the CBCT exposure date.

\*\* Exclusion criteria: previous traumatic dental injuries towards the anterior maxilla, craniofacial syndromes, cleft lip and/or palate, presence of mesiodens, odontomas or cysts, ongoing orthodontic treatment and/or fixed appliances, and patients with improper journal documentation.

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### *Radiographic modalities*

In *Paper I*, four radiographic devices were assessed. The CBCT units included were: A NewTom 5G (Quantitative Radiology Srl, Verona, Italy) operating at 110 kV (72 mAs) ; A Promax 3D Classic (Planmeca Oy, Helsinki, Finland) operating at 90 kV (109 mAs). The panoramic device included was: A Promax 2D (Planmeca Oy), 62 kV (42 mAs). The intraoral device included was: Prostyle Intra (Planmeca Oy), 66 kV, (0.8 mAs). In *Paper II*, the Planmeca Promax 3D MID (Planmeca Oy) was used. In *Paper III*, the CBCT units used were the Promax3D (Planmeca Oy), the 3D Accuitomo-XYZ Slice View Tomography (J. Morita Corp, Kyoto, Japan) and NewTom 3G (Quantitative Radiology Srl). The intraoral, panorama and cephalometric devices varied, depending on the referring instance.

The panoramic radiographs in *Paper I* were taken with a child collimation. Additionally, both a central maxillary incisor projection and a maxillary lateral projection were taken with the intraoral device. For both *Paper I* and *II*, the CBCT volumes were centred on the anterior maxilla, where impacted canines are located. The FOVs ranged from Promax's 4 x 5 cm – NewTom's 6 x 6 cm in *Paper I* to Promax's 4 x 5 cm in *Paper II*, and all chosen FOVs were each individual unit's smallest FOV option. As *Paper III* assessed retrospective material, the FOV's ranged according to the standard at the time as well as the individual clinician's preference.

### *Radiographic assessment*

In *Paper II*, all volumes were individually evaluated in a random order by five experienced specialists in dentomaxillofacial radiology. After a minimum time-lag of three weeks, 25% of the volumes were reevaluated to measure intra-observer agreement. In *Paper III*, prior to the therapy planning session, two maxillofacial radiologists jointly performed the radiographic assessment for all 2D images according to a protocol, and then after a time lag of six months, the same assessment was done for all the 3D images.



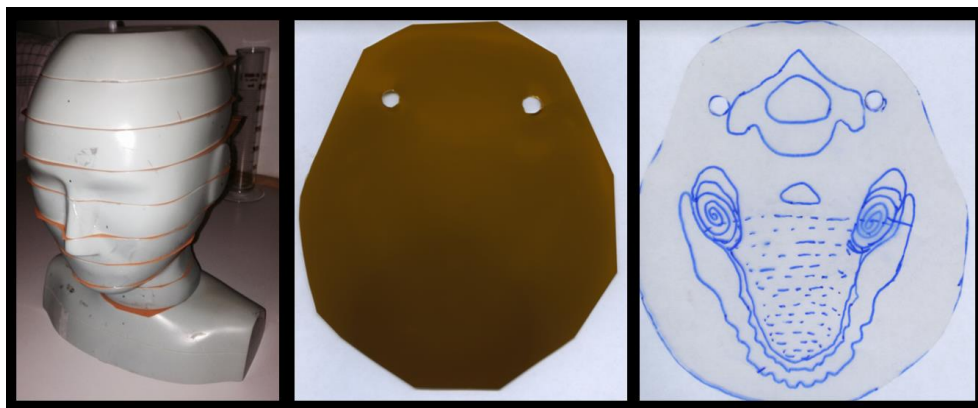
*Image evaluation conditions*

In both *Paper II* and *Paper III*, all images were examined under identical viewing conditions, in a dimly lit room with a 19-inch screen with 1280 × 1024 definition (Eizo Flexscan, model MX190, EIZO Nanao Corporation, Hakui, Ishikawa, Japan). The screen display was adjusted to the Digital Imaging and Communications in Medicine (DICOM) mode as described by Barten.<sup>69</sup> Image manipulation was allowed, so the observers could assess the radiographs according to their individual preferences, with no time limit. In *Paper II*, observers were blinded to the protocol and phantom number and in *Paper III*, all observers were blinded at the patient level. During radiographic assessment in *Paper III*, the observers did not have access to CBCT images during the 2D evaluation.

## 4.2 Paper I

### *Dosimetry*

TLD-100 thermoluminescent dosimeters (TLDs) were used to measure organ doses from CBCT images (ProMax3D and NewTom5G). GafChromic-QR2 dosimetric film (International Speciality Products, Wayne, NJ) was used to measure organ doses from the panoramic and intraoral units, as well as the NewTom5G. Both TLD and GafChromic film measurements were used for the NewTom5G in order to compare the two methods. Both methods were calibrated in a standardised manner according to AAPM.<sup>70</sup> Since the NewTom5G CBCT unit had the largest X-ray field of all the examined X-ray devices, this unit is expected to have the least uncertainty caused by the detector position, and was thus chosen for comparing the TLD and GafChromic film methods. Organ outlines were used as guides for all modality measurements, both for TLD measurement point placement as well as organ location for film dosimetry (Figure 5).



**Fig. 5** An illustration of the phantom from *Paper I* with GafChromic film placed between the slices, GafChromic film after CBCT exposure, and an example of an organ outline.

### *Thermoluminescent Dosimeters*

A total of 68 TLDs were placed at 34 measurement points throughout the top 10 slides of the phantom, which encompass the head and neck region. Two TLDs were positioned at each measurement site. 17 sites were used to measure both the active marrow and the endosteum, 11 sites were used to measure the brain, 5 sites were used to measure the lymphatic nodes, 4 sites were used to measure the salivary glands, 3 sites were used to measure both the extrathoracic airways and the oral mucosa, and 2 sites were used to measure both the thyroid and the oesophagus.

Prior to taking each measurement, the TLDs were annealed first for 1 h at 400° C, and then for 4 h at 100° C. After irradiation exposure(s), the TLDs were removed from the phantom and measurements were read with a Harshaw 5500 (Thermo Scientific, Waltham, MA) TLD reader.

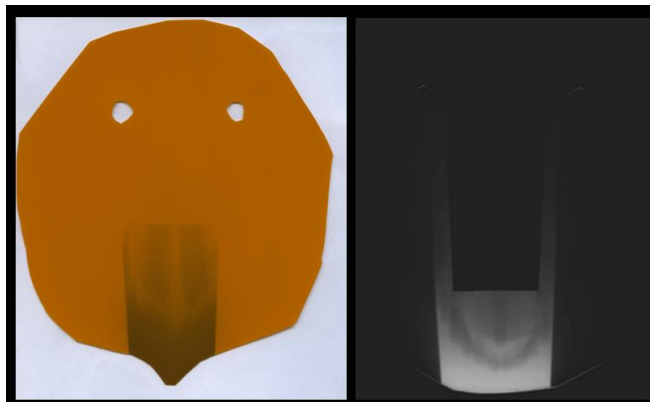
The resulting dose measurements for all devices were an average of multiple doses delivered, determined by dividing the dose sums by the number of exposures needed to obtain a reading from the TLDs. A total of 160 exposures were obtained for the intraoral examination, 50 exposures for the panoramic image, and 20 exposures for each CBCT unit.

### *GafChromic film*

GafChromic-QR2 dosimetric film (International Specialty Products, Wayne, USA) was placed between each slice and covered the slice's entire surface area. The film was read with an Epson Perfection 7000 flat-bed scanner (Seiko Epson Corporation, Suwa, Japan), then analysed in ImageJ (National Institutes of Health, Bethesda, MD). Simultaneously as the GafChromic dose measurements were taken, a non-irradiated background film was also read. The difference in pixel value of the GafChromic film compared to the mean value of the background film was considered to be the film signal. The signal-to-dose response of GafChromic film is non-linear, and dose-response calibration curves were used individually for each radiographic device to determine the mean dose of all the pixels within the delineated organ area.

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Correcting the beam attenuation within the intraoral sensor was necessary for the intraoral radiograph measurements since the detector functions as a dose-absorbing shield. The dose to the area shielded by the detector was divided by the transmission through the sensor (Figure 6), which was 4.5%.<sup>71</sup>



**Fig. 6.** The film response for a central incisor periapical radiograph compared with the dose map after background correction, dose-response calibration and sensor attenuation correction.

### *Dose calculations*

All measurements were converted into dose to the surrogate tissue, according to the International Committee on Radiological Units and the AAMP protocol.<sup>70</sup> The effective dose was then calculated according to the ICRP 103 to compare the different radiographic modalities.<sup>45</sup> The dose to organs outside the region of the head and neck were negligible. These organs, as well as organs estimated to contribute less than 1% to the effective dose (skin and muscle) were considered as contributing zero effective dose. To calculate the mean organ dose for organs only partially placed in the head and neck region, the measured organ dose was multiplied with the fraction of the organ within the head and neck while the fraction of the organ outside the head and neck was assumed to be zero.

**Table 3.** Fractions used for a 10-year-old child

Tissue	Fraction	Source
Active Marrow		
Cranium	11.6%	Cristy <sup>72</sup>
Mandible	1.1%	Cristy <sup>72</sup>
Cervical Vertebrae	2.7%	Cristy <sup>72</sup>
Endosteum		
Cranium	24.9%	TM50 fractions*
Mandible	0.6%	TM50 fractions*
Cervical Vertebrae	1.5%	TM50 fractions*
Lymphatic node	6.3%	ICRP computational phantom**
Oesophagus	10%	ICRP computational phantom**

\*The fractions for TM50 were estimated by scaling the fractions for an adult male in the ICRP

computational phantom with the active marrow ratio between an adult male and a 10-year-old child

reported by Cristy.<sup>72</sup>

\*\*Based on an adult male

To compare doses between modalities, the effective dose measurement for each separate modality were calculated by multiplying the equivalent dose for a tissue with its tissue weighting factor, according to the ICRP 103 measurements adjusted to 10-year-old fraction estimates, and then summing the equivalent doses for all measured tissues (Table 3).

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### 4.3 Paper II

#### *Protocols*

To optimise the dose/image quality of the Planmeca Promax 3D MID according to the clinical task of evaluating impacted maxillary canines, six different dose levels were tested. A total of 48 volumes were obtained, one of each protocol on each specimen's anterior maxilla. The protocol parameters can be seen in Table 4. The kV filtration and FOV were consistent for all protocols, while the tube current varied between 2.5 mA and 10.0 mA.

The first protocol is the standard protocol, which is the protocol that was currently used at Karolinska Institutet, Sweden, for evaluating impacted maxillary canines. The second protocol is a high-definition protocol, often used in endodontics due to the better spatial resolution. Four low-dose protocols were also tested. Of these, two are Planmeca's own default ultra-low-dose protocols. These low-dose protocols combine reduced mAs with a lower number of pulsed exposures, which reduces dose but also introduces a reduced SNR in the resulting image. Planmeca compensates for the noise caused by low mAs and fewer projections by automatically applying a noise reduction filter to their default low-dose protocols. The noise reduction filter is called "the Adaptive Image Noise Optimiser" or [AINO] filter.

In addition to Planmeca's low-dose protocols, two more low dose protocols were created, both having comparable doses to Planmeca's own protocols, except without the AINO noise reduction filter. These dose-equivalent protocols were analysed to test if Planmeca's AINO filter improves diagnostic performance.

**Table 4.** Exposure Protocols

Protocol	Type	Definition	kV	mAs	Voxel size [µm]	Frames	Nominal DAP [mGycm <sup>2</sup> ]	Dose fraction to the default %
SD*	Standard	Normal	90	96	200	400	329	100%
HD*	Standard	HD	90	150	150	500	514	156%
ULDHD*	ULD	HD	90	36	150	500	122	37%
ULD*	ULD	Normal	90	23	200	400	77	23%
LDHD	LD**	HD	90	38	150	500	129	39%
LD	LD**	Normal	90	22	200	400	74	22%

\*Manufacturer's default protocols: High Definition (HD), Standard Definition (SD): current clinical default for impacted canine examination, Ultra-low-dose High Definition (ULD-HD), Ultra-low-dose (ULD).

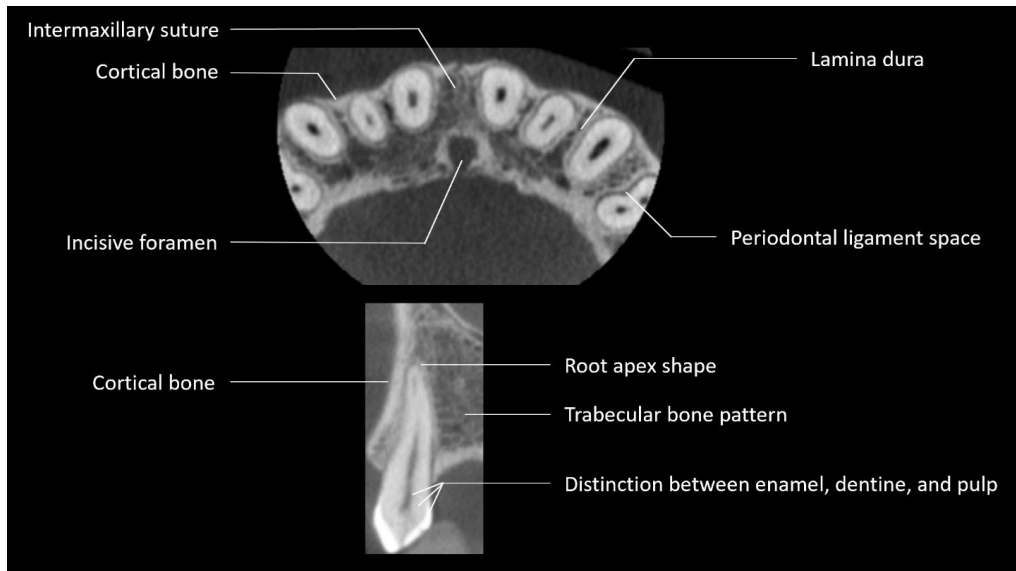
\*\* *Low dose* (LD) indicates equivalent dose level to ULD protocols, but without the quality enhancement algorithm of ULD.

#### *Dose-area product measurements*

DAP values were measured independently, and the measurements were used to compare the dose burden between protocols. Under the conditions of this study, DAP and effective dose are directly proportional to each other.

#### *Image evaluation*

All possible anatomical landmarks in the maxillary front region were included for the evaluation as seen in Figure 7. These landmarks provide information about the canine position or possible root resorptions that is vital for orthodontic therapy planning.<sup>73</sup>



**Fig. 7.** Anatomical structures of interest assessed in dry skull phantoms, seen here in both an axial and coronal view of the HD protocol.

Prior to evaluation, detailed instructions about the assessment criteria were given to all observers. The visibility of the structures was ranked on an ordinal scale of 1 to 4, in which 1 indicated poor visibility, 2 indicated questionable visibility, 3 indicated diagnostically acceptable visibility for the task of assessing impacted maxillary canines, and 4 indicated distinct/excellent visibility. Each observer also rated their overall impression of the image quality, according to the same scale of 1 - 4.



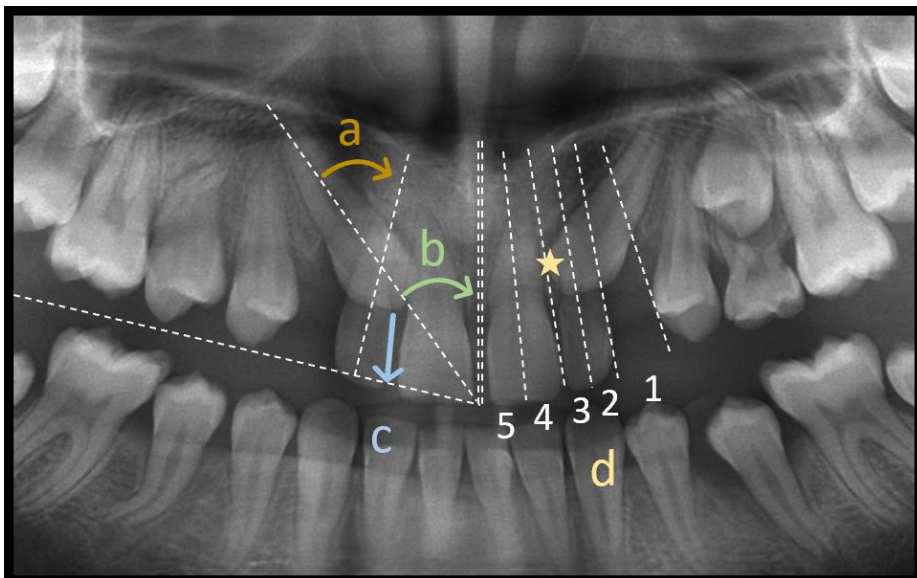
#### 4.4 Paper III

Each of the 89 patient cases included in *Paper III* had a CBCT and a panoramic image taken within a nine-month cut-off period from the date of CBCT exposure. All additional periapical intraoral images and cephalograms taken within the same nine-month cut-off period were also included.

##### *Assessment protocols 2D and 3D*

The protocol used for the radiographic assessment consisted of the following radiographic variables:

- The canine eruption angulation was assessed as being normal / vertical, mesio-angular, horizontal, disto-angular, inverse, or uncertain.
- The canine cusp position was assessed as central, buccal, or palatal in the bucco-palatal plane, or uncertain.
- The canine root development stage was assessed as ongoing / open apex, closing apex / completely developed apex, or uncertain.
- The presence of root resorption on the lateral incisor was determined as either present, not present, or uncertain. If present, the location options were on the cervical, middle, or apical third of the root or a combination and the depth of the resorption was determined as mild (less than 1/3 of the dentine), moderate (more than 1/3 of the dentine, but not involving the pulp), and deep (involving the pulp).
- The presence of anomalies, including dilacerated roots, atypical root morphology, or ankylosis.
- Different variables were also measured in the panoramic image, as seen in Figure 8.



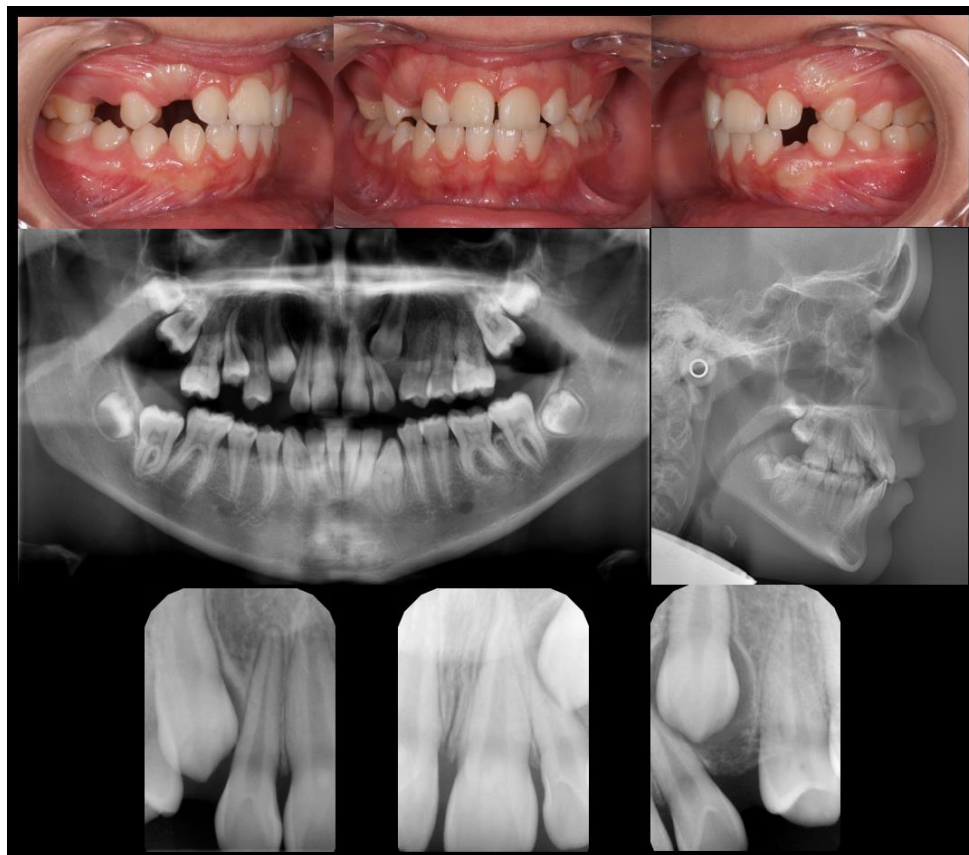
**Fig. 8.** Different variables measured from the panoramic image. a: The angle between the canine midline and the adjacent lateral incisor midline, measured in degrees; b: The angle between the canine midline and the maxillary midline, measured in degrees; c: the distance between the canine cusp tip and the occlusal line, measured in millimetres; d: the most medial position of the canine cusp, as defined by the five numbered sectors. These variables were based on previous studies.<sup>74, 75</sup>

The radiographic assessment results were visualised separately in coded PowerPoint® presentations together with de-identified clinical photos and information about the patient's age, gender, and anamnesis.

#### *Interdisciplinary therapeutic planning*

For each case, a pair of PowerPoint® presentations were made. The first presentation consisted of patient information, clinical photos, and registered diagnostic information based on the 2D radiographs. The second presentation included referral information and registered diagnostic information based on the 3D radiographs. A week prior to the first group therapy planning session, all individual members of an interdisciplinary advisory board received the unidentified 2D case materials to familiarise themselves with the cases. The expert panel consisted of the two radiologists who performed the

initial assessment as well as two orthodontists and a paediatric dental surgeon, each with 10+ years of experience in their specialty. Once the group was familiar with the cases, all the specialists gathered to evaluate each case together as a group.



**Fig. 9.** A typical patient case shown during the 2D case presentations, consisting of clinical photos, a panoramic image, and intraoral periapical images as well as a cephalometric image when available.

The 2D evaluation was presented to the expert group as a virtual case (Figure 9). The expert group held a discussion, and then formed a treatment plan based on consensus, according to the 10 predefined treatment alternatives seen in Table 5.

**Table 5.** Treatment choice options for impacted maxillary canines. The highlighted cells indicate therapy choices involving extractions of permanent teeth.

Treatment Type		Choice #	
Active orthodontic treatment	No surgical exposure	Non extraction	1
		Extraction premolar	2
		Extraction maxillary lateral incisor	3
	Surgical exposure and extrusion	Non extraction	4
		Extraction premolar	5
		Extraction maxillary lateral incisor	6
		Extraction the impacted canine	7
No orthodontic treatment	Observation	8	
	Extraction deciduous canine	9	
Other		10	

Observers then selected an orthodontic approach for space management from the following options: Expansion and levelling, space closure and levelling, or not relevant.

Immediately after the 2D part, the second 3D part of the virtual case presentation was assessed by the expert group and volumetric images were demonstrated for the group by the dentomaxillofacial radiologists. The expert group held another discussion and performed the therapy planning again, based on the same therapy planning questions above, and additionally ranked the level of CBCT indication on the following scale: 1. Definitely not indicated, 2. Probably not indicated, 3. Uncertain, 4. Probably indicated, or 5. Definitely indicated. For subsequent logistic regression analyses, “definitely not indicated” and “probably not indicated” answers were considered as CBCT not being justified, while “unsure”, “probably indicated”, and “definitely indicated” were considered as CBCT being justified.

## 4.5 Statistics

### *Paper I*

Descriptive statistics were used to quantify and compare TLDs and GafChromic film measurements. These statistics included mean values, standard deviations, and polynomial plots for the signal-dose function.

### *Paper II*

One-sample Wilcoxon signed rank test was used to determine the overall subjective image quality of each CBCT protocol as well as the visibility of the anatomic structures located in the anterior maxilla. The most common score value of all observers' answers was seen as representative for each protocol and was used for data analysis. The optimised exposure protocol intended for maxillary canine assessment was defined as the lowest dose protocol where all structures and overall image quality scored as at least acceptable (score of "3"). Thus, a hypothetical median of "3" was the cut-off for diagnostic acceptability. A P-value < 0.05 was considered statistically significant.

Additionally, intra- and inter-observer variability were analysed using Cohen's weighted kappa, according to the Landis and Koch scale for observer agreement in assessing categorical data.<sup>76</sup>

### *Paper III*

Clinical, radiographic, or therapy-based variables based on the 2D therapy discussion were evaluated using a crude logistic regression model to identify when CBCT was considered justified. A stepwise logistic regression model was then used to identify if multiple variables were statistically significant, and this model was applied to not over-fit the adjusted model including non-significant variables. The significance level for entering a variable was set to 0.15, while the significance for removing the variable from the model was set to 0.3. Robust variance estimates adjusting for the bilaterality were used since 43 patients had bilateral impaction.

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## 4.6 Ethical considerations

### *Paper I*

No ethical approval was required as this study was performed on an anthropomorphic child phantom.

### *Paper II*

The Regional Ethical Review Board in Stockholm, Sweden (Daybook no. [Dnr.] 2007/1288-31/2) concluded that this study had no potentially conflicting ethical aspects, even though human biological material was used. The eight human dry skulls used in this study from the Karolinska Institutet had no registration of the eight human dry skulls origin and could not be traced back to the deceased person. However, ethical approval was granted by the Regional Ethical Committee in Norway (REK) (Daybook no. [Dnr.] 161998).

### *Paper III*

This study is retrospective, using radiographs that have already been taken. The clinical examination procedure and patient treatment were not affected. However, for evaluation of possible effects of CBCT on therapeutic planning, access to patient journals and clinical models was needed. For this purpose, an ethical approval was required. The original study design, as well as two amendments to the original application, were approved by the Regional Ethical Review Board in Stockholm, Sweden (Daybook no. [Dnr.] 2007/1288-31/2, 2015/242-32 and 2020-00676. The first amendment was to allow continuation of the project without written consent from the retrospective patients included in the study. The second amendment was to allow inclusion of more patients from an additional clinic. REK also approved this study after all adjustments (Daybook no. [Dnr.] 77310).

## 5 RESULTS

### 5.1 Paper I

The results calculated for one individual image exposed by each modality are shown in Table 6. Standard 2D examinations vary depending on the dental status of the patient. In the case of a unilateral canine impaction, the 2D radiographic examination is comprised of two periapical images with “different projections”, resulting in a combined effective dose of 1.3  $\mu\text{Sv}$ , while a bilateral impaction consisting of three periapical images results in 1.8  $\mu\text{Sv}$ . Both unilateral or bilateral canine impactions may require an additional panoramic image, resulting in combined effective doses of 5.3  $\mu\text{Sv}$  and 6.0  $\mu\text{Sv}$ , respectively.

**Table 6.** Effective dose according to modality

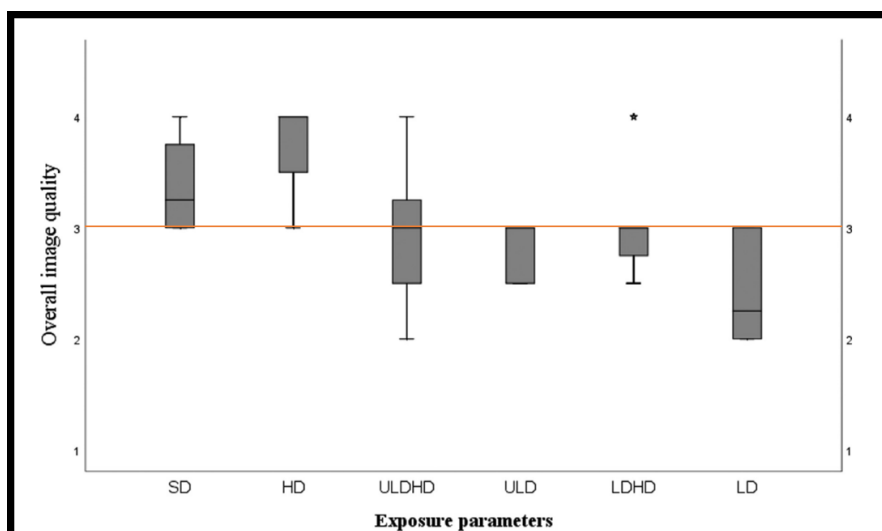
Device (Projection)	Modality	Dosimeter	Image size/ FOV [cm]	Effective dose [ $\mu\text{Sv}$ ]	DAP [mGycm <sup>2</sup> ]
Promax 3D	CBCT	TLD	4 x 5	88 $\pm$ 15	510
NewTom 5G	CBCT	TLD	6 x 6	172 $\pm$ 31	1080
NewTom 5G	CBCT	Film	6 x 6	166 $\pm$ 29	1080
Promax 2D	Panorama	Film	19.2 x 9.2	4.1 $\pm$ 0.8	21.9
Prostyle (Periapical lateral)	Intraoral	Film	4.5 x 5.5	0.6 $\pm$ 0.1	7.42
Prostyle (Periapical central)	Intraoral	Film	4.5 x 5.5	0.7 $\pm$ 0.2	7.42

Resulting effected doses are shown with combined standard uncertainties ( $k=1$ ).

A CBCT examination resulted in 15 times to 140 times higher doses than a complete 2D-examination, depending on the CBCT device and the 2D examination type. A NewTom 5G examination resulted in 140 times higher dose when compared to the most minimal 2D examination requiring a lateral periapical intraoral image and a central periapical intraoral image, while a Promax 3D examination resulted in 70 times higher dose. A NewTom 5G examination resulted in roughly 30 times higher dose, while a Promax 3D examination resulted in roughly 15 times higher dose when compared to the 2D examination requiring two lateral periapical intraoral images, a central periapical intraoral image, and a panoramic image.

## 5.2 Paper II

All tested protocol rankings for overall image quality are illustrated in Figure 10. The SD and HD protocols ranked highest regarding overall image quality, however these two protocols also had the highest radiation burden of the six tested. The two protocols that had the AINO noise reduction filter applied to them (ULDHD and LDHD) ranked higher than their dose-equivalent protocols without the AINO filter (ULD and LD, respectively).



**Fig.10.** The overall image quality according to the applied protocols. SD, standard definition; HD, high definition; ULDHD, ultra-low dose with high definition; ULD, ultra-low-dose; LDHD, low-dose with high definition; LD, low-dose. The top of the box represents the 75th percentile; the bottom of the box represents the 25th percentile, and the middle line represents the median. The whiskers extend from minimum to maximum values, excluding outliers or extreme values. The star beyond the whisker represents an outlier. The majority of the observers scores were considered representative, and each protocol included eight data points representing one majority score per phantom. The orange line represents a hypothetical cut-off value of “3” (acceptable image quality).



As seen in Table 7, the HD protocol had significantly higher medians than “3” for both overall image quality and anatomic structure visualisation, indicating that this protocol is overqualified. The LD protocol had a significantly lower median values than the hypothetical diagnostically acceptable value of “3”, both for overall image quality and for the intermaxillary suture, trabecular bone pattern, lamina dura and periodontal ligament space. With regards to the visibility of anatomical structures, the LDHD protocol had a significantly lower median value than “3” for the precision of identifying the intermaxillary suture ( $p = 0.02$ ).

**Table 7.** One-sample Wilcoxon signed Rank test for image quality and structure visualisation

	SD Median (Sig. <sup>a,b</sup> )	HD Median (Sig. <sup>a,b</sup> )	ULDHD Median (Sig. <sup>a,b</sup> )	ULD Median (Sig. <sup>a,b</sup> )	LDHD Median (Sig. <sup>a,b</sup> )	LD Median (Sig. <sup>a,b</sup> )
Overall image quality	3.25 (0.063)	4.00 (0.014)	3.00 (0.783)	3.00 (1.000)	3.00 (0.083)	2.25 (0.034)
Maxillary suture	3.00 (0.705)	3.25 (0.098)	2.00 (0.086)	2.00 (0.079)	2.00 (0.020)	2.00 (0.017)
Trabecular bone	3.25 (0.258)	4.00 (0.019)	3.00 (0.748)	2.00 (0.067)	3.00 (0.102)	2.00 (0.011)
Cortical bone	3.50 (0.015)	4.00 (0.007)	3.50 (0.038)	3.75 (0.052)	3.00 (0.257)	3.00 (0.257)
Foramen incisivum	4.00 (0.005)	4.00 (0.005)	4.00 (0.014)	4.00 (0.025)	3.00 (0.317)	3.00 (0.083)
Enamel-dentin-pulp	3.50 (0.046)	4.00 (0.008)	3.50 (0.023)	3.50 (0.034)	3.50 (0.034)	3.00 (0.157)
Lamina dura	3.00 (1.000)	3.75 (0.052)	3.00 (0.458)	2.75 (0.098)	2.75 (0.129)	2.00 (0.014)
Periodontal ligament	3.25 (0.234)	4.00 (0.020)	3.25 (0.408)	2.00 (0.058)	2.75 (0.059)	2.00 (0.014)
Apex	4.00 (0.025)	4.00 (0.005)	3.25 (0.059)	3.00 (0.180)	3.00 (0.180)	3.00 (0.655)

- The significance level is 0.050.
- Asymptotic significance is displayed.

The overall image quality and the visibility of each anatomic structure using the hypothetical median “3” (diagnostically acceptable) for the tested exposure protocols. The observed medians and their p-values are listed for each protocol. Data marked in orange indicate the observed medians are significantly lower than 3, whereas data marked in blue indicate the observed medians are significantly higher than 3.

The intra-observer agreement of overall image quality had a mean of 0.395 and ranged from 0.286 to 0.471 (fair to moderate), and intra-observer agreement regarding the

anatomic structure visibility had a mean of 0.547 and ranged from 0.485 to 0.66 (moderate to substantial).

The pairwise inter-observer agreement based on the 5 observers regarding overall image quality resulted in a mean of 0.350 and ranged from 0.167 to 0.513 (poor to moderate). Regarding anatomic structure visibility, the mean was 0.370 and ranged from 0.135 to 0.537 (poor to moderate).

### 5.3 Paper III

70 of 132 (53%) of the cases did not have an indication for obtaining a CBCT based on the 3D material. The therapy choice changed for 13 of 132 impacted teeth (9.8%) after additional diagnostic information from 3D imaging (Table 8). Of these, the therapy changed from non-extractions to extraction therapy in six cases. Additionally, six cases changed from extracting premolars to extracting lateral incisors or the impacted canine. In one case, the therapy changed from extracting the impacted canine to extracting the central incisor.

**Table 8.** Therapy choice differences at the tooth level.

Therapy Choice* 2D	Therapy Choice* 3D									
	1	2	3	4	5	6	7	8	9	10
1	2	-	-	-	-	-	-	-	-	-
2	-	6	2	-	-	-	-	-	-	-
3	-	-	2	-	-	-	-	-	-	-
4	-	-	-	49	-	2	1	-	-	-
5	-	-	-	-	10	3	1	-	-	-
6	-	-	-	-	-	5	-	-	-	-
7	-	-	-	-	-	-	22	-	-	1
8	-	-	1	-	-	-	-	6	-	-
9	-	-	1	-	-	-	1	-	16	-
10	-	-	-	-	-	-	-	-	-	1

\*Therapy number as according to Table 5. Treatment choice options for impacted maxillary canines, page 37.

Of the predicted variables that were measurable in the 2D case material, horizontal angulation of the canine when compared to vertical angulation, extraction strategy involvement of permanent teeth, and buccally positioned canines when compared to all other positions (palatal, central, and distal or uncertain positions) were significant 2D predictors for CBCT justification (Table 9).

The variables that were considered in the stepwise multivariable prediction model for CBCT indication were: 1) Eruption angle of the canine, 2) Canine crown position, 3) Root development stage, 4) Severity of CIRR, 5) Extraction therapy, and 6) Space management, all with a P value < 0.05 in the ordinary crude model. No patient related predictors such as gender, age, or whether the impaction was unilateral or bilateral were seen as significant in the crude analysis. Of the radiographic and therapy-related predictors, the medial position of the canine crown, the angulation of the canine eruption to the lateral incisor, the distance in millimetres of the cusp to the occlusal line of the maxilla, and the space management alternatives were not found to be significant in the crude analysis and was not included in the stepwise regression analysis.

The stage of root development was not found to be statistically significant in the stepwise analysis, and a moderate, deep, or uncertain severity of CIRR was seen to be negatively correlated with CBCT justification.

**Table 9** Stepwise regression analysis of 2D session variables for CBCT indication

Predicted variables	Stepwise	
	OR (95% CI)	P Value
<u>2D radiographic predictors</u>		
Eruption angulation of canine		
Vertical	1	ref
Mesioangular	1.56 (0.42 - 5.79)	0.504
Horizontal	10.92 (1.65 - 72.42)	0.013
Canine crown position		
Central	0.04 (0.01 - 0.26)	0.001
Buccal	1	ref
Palatal	0.19 (0.04 - 0.98)	0.047
Uncertain / Distal	0.13 (0.03 - 0.53)	0.005
Severity of CIRR		
None	1	ref
Mild	0.22 (0.01 - 3.82)	0.295
Moderate, Deep, or Uncertain	0.12 (0.03 - 0.52)	0.005
<u>Therapy related predictors</u>		
Extraction therapy of permanent teeth		
Yes	1	ref
No	0.15 (0.04 - 0.58)	0.006

2D, Two-Dimensional; CBCT, Cone-Beam Computed Tomography; CIRR, Canine Induced Root Resorption.

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## 6 DISCUSSION

### 6.1 General Discussion

This thesis focused on CBCT examinations of impacted maxillary canines from three different aspects: the dose level, possibilities to optimise examination protocols, and the justification process for CBCT application.

The diagnostics and therapy planning of impacted canines often can be reached by obtaining conventional 2D images, i.e. two periapical radiographs and a panoramic radiograph. Not all information inherent in 3D imaging translates to a benefit for the patient with respect to diagnostics, choice of therapy planning, treatment outcome, and societal costs.

In accordance with the ALARA principle, optimised protocols that are applied according to clear justifications may lower the dose burden on a population level.<sup>25, 45</sup> However, even when it is possible to maintain an acceptable diagnostic image while reducing the dose a third of the dose recommended by manufacturers as shown in *Paper II*, CBCT examinations still expose patients to a much higher dose than conventional 2D radiographs.

Therefore, justification of CBCT use, especially regarding children, is of importance. *Paper III* results imply that clear clinical guidelines for applying CBCT may potentially limit dose exposure when such guidelines take into consideration what information is diagnostically necessary to obtain for therapeutic planning as part of the justification process, thereby limiting CBCT examinations to the clinical situations where there is a benefit to the patients. The specialty of dentomaxillofacial radiology doesn't yet exist in all countries worldwide, and the benefit of well-grounded guidelines can be helpful for other specialists and general dentists, especially regarding radiation protection considerations.

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### *Paper I*

Via dosimetry, this thesis investigated the differences in effective doses for paediatric patients receiving radiographic examinations intended for impacted maxillary canines. *Paper I* demonstrated a dramatically increased risk of radiation-induced cancer if a CBCT was taken instead of two periapical radiographs. Previous studies using different CBCT devices to investigate the effective dose of paediatric examinations on anthropomorphic phantoms have a range of resulting effective doses. Marcu et al. utilized an 8-year-old voxelized phantom to assess the effective dose of a 4.2 x 5.5 cm FOV examination of impacted maxillary canines using Monte Carlo simulations.<sup>77</sup> When using a protocol of 96 kV and 96 mAs, the effective dose the 8-year old phantom was exposed to was 125  $\mu$ Sv. Optimised exposure doses will vary between different CBCT units, however much of this can be explained by differences in FOV size and applied filter thickness. By scaling our results, to the same kV, mAs and FOV, performed by a medical physicist using the SpekCalc software by Gavin Poludniowski, our estimated result is 113  $\mu$ Sv, which is within one standard uncertainty of Marcu et al's results.<sup>78, 79</sup>

### *Paper II*

Visually pleasing images in radiology can subjectively be seen as superior in terms of image quality, despite lower-definition images possibly sufficing for the diagnostic task at hand.<sup>42</sup> In certain clinical situations, a HD protocol may be necessary for diagnostic and treatment purposes, however in *Paper II*, the HD protocol had the highest radiation burden of all the protocols and was assessed as overqualified for viewing the anatomical landmarks in the maxillary front. Three of the low-dose protocols tested, the ULDHD, ULD, and LDHD protocols, could replace the HD and SD protocols, as they provided diagnostically acceptable image quality while reducing the dose by 63%, 77%, and 61% respectively. However, of these protocols, the LDHD provided poor visibility of fine structures, including the intermaxillary suture, trabecular bone pattern, lamina dura, and periodontal ligament space. In clinical situations where these structures are important for the continuing treatment, the LDHD protocol is not diagnostically acceptable. The ULD and LD protocols had comparable

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dose levels (77 mGycm<sup>2</sup> for ULD and 74 mGycm<sup>2</sup> for LD). The LD protocol stood out as insufficient, however inferior image quality was not observed in the ULD protocol, indicating that a noise reduction filter may compensate for the reduced SNR in low-dose protocols.

### *Paper III*

There is no clear consensus, currently, over whether 3D images lead to a different therapy plan for impacted canines when compared to 2D images. Some studies support that CBCT examinations do lead to a change in treatment.<sup>80, 81</sup> Other studies, including *Paper III* do not.<sup>82</sup> When considering whether CBCT is indicated for therapeutic thinking, root resorptions were not seen to be a significant variable independently. However, when extraction strategy was involved, the OR of needing a CBCT increased to 6.7 when compared to situations where extractions weren't part of the therapy plan. If extraction strategy is involved in the management of the canine, knowledge of resorptions becomes essential since there is a substantial risk of extracting healthy premolars instead of severely resorbed incisors.<sup>14</sup>

## 6.2 Interpretation of major findings

The manufacturer's recommended protocols were used for *Paper I*, under the assumptions that 1) high definition was needed for impacted canine assessment in order to visualize fine details in anatomic structures and 2) that low noise levels would be required in order to detect mild root resorptions.<sup>31, 83, 84</sup> While the CBCT protocols in *Paper I* were not optimised, results for optimised protocols can be estimated by converting the DAP to effective dose using the low-dose protocols of *Paper II* (Table 10). Estimating the effective dose based on the DAP values is possible since the applied CBCT device and tube potential were the same.

**Table 10.** Effective dose according to different CBCT units and protocols

Device (Projection)	Protocol	Image size/ FOV [cm]	Effective dose [ $\mu$ Sv]	DAP [mGycm <sup>2</sup> ]
Promax 3D Classic	Standard	4 x 5	88	510
NewTom 5G	Standard	6 x 6	166 - 172	1080
Promax 3D MID	HD	4 x 5	89*	514
Promax 3D MID	Standard	4 x 5	57*	329
Promax 3D MID	ULDHD	4 x 5	21*	122
Promax 3D MID	ULD	4 x 5	13*	77
Promax 3D MID	LDHD	4 x 5	22*	129

\*Effective dose scaled proportional to DAP values and Promax 3D MID protocol parameters.

The comparable effective dose estimates for the low-dose protocols imply that instead of 15 – 140 times the dose when compared to 2D conventional examinations, the ULDHD protocol has 4 – 16 times the dose, the ULD protocol has 2 - 10 times the dose and the LDHD protocol has 4 – 17 times the dose.

Previously, Hidalgo Rivas et al. investigated the potential for lowering CBCT dose when assessing root resorptions caused by impacted maxillary canines and found that



by reducing the kV and mAs using an Accuimoto device, the DAP could be lowered to 146 mGycm<sup>2</sup>.<sup>85</sup> This DAP is comparable to the low-dose protocols from *Paper II*, further supporting the possibility of applying optimised low-dose protocols for maxillary canine assessment.

While some low-dose protocols may be optimal in assessing impacted canines, this does not exclude the need for better image resolution in some clinical situations where fine structure details are of concern for the following treatment plan. The optimization process shall be performed on an individual basis.<sup>31</sup> Dose optimisation is not merely an intention to lower radiation doses at all costs. The diagnostic requirements of the clinical task at hand determine the dose level needed for a diagnostically acceptable image.

To our knowledge, no studies have assessed how interdisciplinary therapy planning influences the CBCT justification process. Results from *Paper III* imply that CBCT exposures can be drastically reduced according to the ALARA principle of justification at the therapeutic thinking level. 2D predictors for needing a CBCT based on therapeutic thinking were found to be horizontally positioned canines, when extraction strategy may be involved as a therapy choice based on 2D examinations, and when canines were positioned buccally.

Typical clinical situations where CBCT was justified were when diagnostic information was required prior to choosing the ideal permanent tooth to extract while not missing suspected root resorptions, as well as prior to extracting horizontally positioned impacted canines.

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### 6.3 Methodological considerations

#### *Assessment of dosimetry*

Previous to the publication of *Paper I*, to our knowledge, there was only one published study on the estimation of paediatric organ and effective dose from CBCT units.<sup>50</sup> In this study, effective dose was measured for a number of CBCT units with various FOV, however the study was not related to a specific diagnostic task. Additionally, in this study too few TLDs were placed on organs that contribute mostly to the effective dose, which may influence the accuracy of the estimation. Dose measurements in *Paper I* were performed on an anthropomorphic phantom, representative of a 10-year-old child, using multiple X-ray units and modalities, task-specific to impacted maxillary canines, quantified by two methods of dosimetry; 68 TLDs and GafChromic film. Panoramic and intraoral images are better measured using GafChromic film, which allows for continuous high-resolution measurements of sharp dose gradients over a large area.

While the TLD method is a widely used method for dosimetry, the method itself is not without limitations.<sup>38, 86</sup> When too few TLDs are used, organ dose measurements become more uncertain. A study using 30 TLDs found that panoramic images may have a higher dose than previously reported, 19 – 75  $\mu\text{Sv}$  depending on the panorama unit used, which is 5 – 18 times more than our results.<sup>87</sup> In *Paper I*, more TLDs were used than in previous similar studies, and the dose measurement agreement when compared to GafChromic film was acceptable.

#### *Assessment of dose-area product*

Comparing DAP under conditions where the FOV size, examination location or X-ray energies or irradiation geometries differ introduces potential errors, and in these situations, using effective dose as a tool of dose comparison is preferred.<sup>45</sup> When using DAP as a comparative method to determine dose differences between protocols for a particular CBCT device, the kV, filtration, FOV size and position must be kept constant to ensure that DAP and the effective dose remain directly proportional, as was the case in *Paper I* and *II*. DAP is a measurement of the dose quantity before photons

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interact with the irradiated tissues, so FOV, location, and the irradiated area are not taken into consideration.

The CBCT protocol used in *Paper I* was the standard protocol recommended by the CBCT unit manufacturers and is also considered a “full dose” protocol. Hidalgo Rivas et al. have previously created multiple low-dose protocols for the assessment of impacted maxillary canines by using variations of kV and mAs parameters.<sup>85</sup> These protocols were then applied using a 4 x 4 FOV exam on an anthropomorphic phantom. Optimal exposure levels were decided by 8 observers who found that the standard recommended protocol’s dose, in terms of DAP, could be halved to 146 mGycm<sup>2</sup>. Similar results were seen in *Paper II*, where the dose was reduced by up to 77%, depending on which anatomic structure is important to visualize in fine detail. The overall DAP levels differ between CBCT units, as the Accuitomo F170 used by Hidalgo Rivas et al. allows for a 4 x 4 cm FOV, while the Planmeca devices used in *Paper I* and *II* had a FOV of 4 x 5 cm.

#### *Assessment of effective dose*

Effective dose measurements shouldn’t be applied to individual risk assessments or risk assessments of inhomogeneous irradiations. The purpose of *Paper I* was not to perform a risk assessment of CBCT examinations for an individual, rather to optimise radiographic evaluations intended for impacted maxillary canines by comparing different modalities, and in this instance, the effective dose is a useful method.<sup>45</sup> When comparing the dose burden of different radiographic modalities, there is a variation between the effective dose and DAP relationship, depending on the area being examined. Because of this, using conversion factors to relate DAP and effective dose to one another has been criticized.<sup>88</sup> Nevertheless, the ICRP recognizes that effective dose measurements can be useful when comparing doses from different modalities that use similar technologies.<sup>89</sup>

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### *Assessment of subjective image quality*

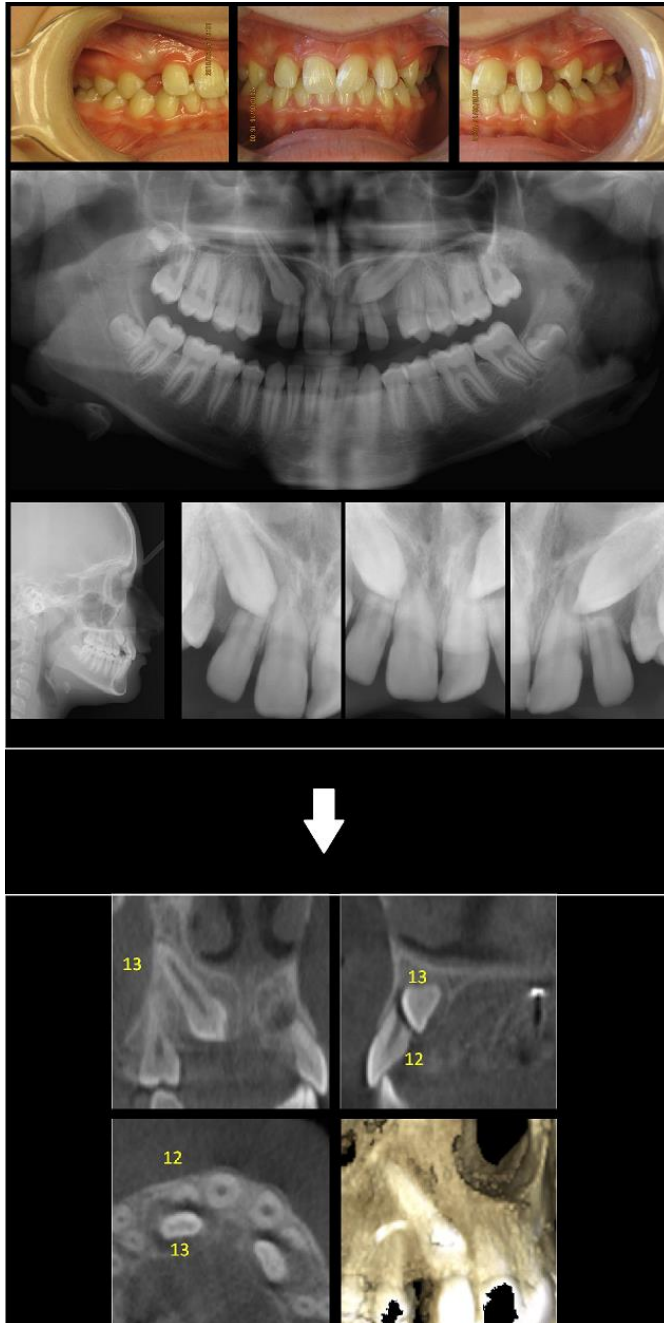
Multiple observers assessed structure visibility and overall protocol image quality in *Paper II* and selected a score from four subjective ranking options: excellent, acceptable, questionable, and poor. The subjective difference between these rankings are not equidistant values, making Cohen's kappa the appropriate statistical method to apply. The degree of disagreement between the scores on the 4-rank scale were significant for our assessment and a weighted Cohen's k-coefficient was thus used to measure the reliability of the intra- and inter-observer agreement.<sup>90</sup> According to the Landis and Koch scale for observer agreement in assessing categorical data, the intra-observer agreement ranged from fair to substantial and pairwise inter-observer agreement ranged from poor to moderate with a large variation (0.167 – 0.513).<sup>76</sup> This suggests that the radiologists had differing subjective preferences, which was expected as subjective preference and image quality varies amongst interpreters. The observers in *Paper II* were not, however, used to viewing low-dose CBCT images and the differences between the low-dose protocols in this study were considered subtle. Additionally, no practical calibration was performed prior to assessment of the CBCT volumes. While the results reflect the clinical reality of subjective image preference variations amongst dentomaxillofacial radiologists, we believe that perceptual training and pre-calibration instead of detailed verbal instructions will result in improved reliability in future studies.

### *Assessment of therapy planning*

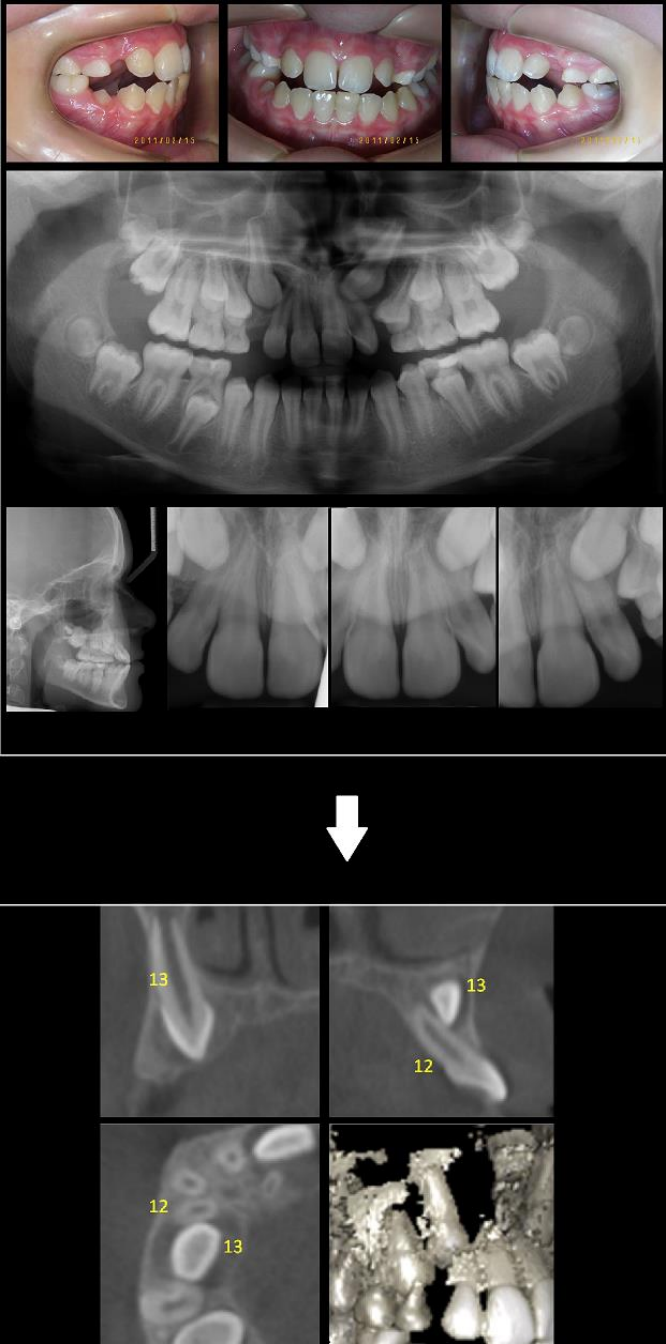
In *Paper III*, 13 cases (9.8%) of the therapy plans changed with additional information from CBCT. This result is similar to a study demonstrating that CBCT influenced the therapy plan in only 12% of mandibular third molars.<sup>91</sup> Of the 13 impacted canine cases that changed therapy plan, all of the cases resulted in a final therapy choice that involved extracting a permanent tooth, and the root status of the adjacent lateral incisor was essential when choosing which permanent tooth was most beneficial to extract. However, not all impacted canine cases in which a more severe root resorption was discovered after CBCT led to a therapy change, despite the worse status of the lateral

incisors root (Figure 11 and 12). CBCT is superior when used to detect root resorptions in comparison to 2D images.<sup>80, 92, 93</sup> However, there is no consensus on whether increased precision of root resorption detection plays any major role in altering or affecting therapeutic thinking.<sup>80-82, 94, 95</sup> When deciding whether to perform a CBCT examination, it is important for clinicians to consider the possible treatment alternatives for the individual patient, and if the preliminary therapy choice requires information about possible root resorptions.

Figure 11 and 12 represent cases where CBCT was not indicated at the therapeutic thinking level, judged by the panel in *Paper III*. When the CBCT referral was originally sent for both cases, there was an indication to take a CBCT based on the referral question of whether root resorption was present. However, at the therapeutic thinking level prior to CBCT, all teeth in Figure 11 would be kept as a part of the preliminary therapy plan regardless of root resorption due to the spacing between the teeth. In Figure 12, all teeth would be kept as a part of the preliminary therapy plan prior to CBCT regardless of root resorption due to the Class III occlusion. Possible root resorption on lateral maxillary incisors did not affect therapeutic thinking at this point in either patient's treatment in Figure 11 or 12.



**Fig. 11.** Images above the arrow are from the 2D session, and the image below the arrow is the reformatted CBCT cross-sections of the same patient.



**Fig. 12.** Images above the arrow are from the 2D session, and the image below the arrow is the reformatted CBCT cross-sections of the same patient.

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### *Assessment of 2D therapy planning markers*

Horizontally placed canines were a significant 2D radiographic predictor for CBCT justification when seen on a panoramic image. The unfavourable position of these canines, usually high up in the hard palate, make intraoral radiographic assessment difficult. When dental paediatric surgeons prepare for extraction or surgical exposure, often an exact location of the tooth is needed, as well as information about surrounding anatomic structures, complicated root morphology, or even ankylosis. While this result is expected, it should nevertheless be interpreted with caution due to few included horizontal impaction cases in the analysed material.<sup>83</sup>

Buccally placed canines were also a significant radiographic predictor for CBCT justification when compared to all other positions in the bucco-palatal plane. Previous studies have shown that buccally palpable canines do not rule out the resorption risk of neighbouring teeth.<sup>96,97</sup> One retrospective study showed 22 patients needing surgical intervention due to impacted teeth showed that buccally displaced canines induced root resorption 50% of the time.<sup>96</sup> A case study based on six patients showed that buccally displaced teeth caused root resorptions 33% of the time.<sup>97</sup> In *Paper III*, buccally placed canines had a 5.26 times higher risk as compared to palatally placed canines for a CBCT being needed for therapy planning.

Extraction strategy was the only important therapy-related predictor confirmed by regression analysis. Preliminary therapy planning involving extraction of permanent teeth increased the need for CBCT. However, root resorptions of adjacent lateral incisors were only an issue when knowledge of a suspected resorption's location and degree were essential for extraction strategy planning, and suspected resorption was not seen in the 2D images. When the preliminary therapy plan involves permanent tooth extraction, or if permanent tooth extraction is an option based on 2D radiographs, alertness to root resorptions is important and this diagnostic information should be requested in CBCT referrals.



### *Assessment of panorama radiograph predictors*

The variables measured in the panoramic image, as seen in Figure 8, were not significant predictors for CBCT justification. The angulation of canine eruption in relation to the focal trough, and difficulties ensuring a correct patient position and head alignment may complicate angle measurement interpretation. The panorama technique is sensitive to patient placement errors.<sup>98</sup> Caution should therefore be taken when interpreting panorama angulations.

### *Strengths*

This thesis evaluated dose exposure levels considering a clinically task specific question, regarding impacted canines. Information about the estimated doses from conventional 2D images compared with 3D images is valuable knowledge for the future understanding of comparing low-dose 3D protocols with 2D examinations, especially as technology advances and 3D doses are further lowered.

Previous research evaluating diagnostic accuracy of CBCT examinations on impacted canines has been performed in vivo, but *Paper II* was the first to our knowledge to focus on image quality. Performing an in vivo study using six different protocols is not ethically practical, however, due to the radiation burden to the patients.

This thesis used an interdisciplinary expert panel to discuss and examine patient cases from three clinics in the same radiographic location. To our knowledge, no study has been previously performed using the collaboration of multiple specialties together in therapy planning of impacted canines.

### *Limitations*

The anthropomorphic phantom used in *Paper I* is constructed with pre-drilled holes, which makes organ placement and measurements difficult to be perfectly representative. Also, variations in anatomy and distributions of organ mass, even within patients that are the same age, contribute to possible estimation errors. These errors can be exaggerated when the FOV being analysed is small, such as in the case of maxillary canine examinations. To ensure as accurate of an estimate as possible,

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organ guides were created and placed between each slice of the phantom. Afterwards, dose measurements for both TLD and GafChromic film were recorded and measured based on the organ placement on the guides.

*Paper II* utilized an in vitro design based on 8 adult dry skull phantoms, none of which had impacted canines. Paediatric dry skulls with impacted canines are difficult to collect. Based on *Paper II's* results, a similar study on image quality assessment based on a 4-rank scale would require at least 8 such phantoms, assuming that a significant difference of 0.5 with a standard deviation of 0.4 is expected. Due to the scanning time of CBCT devices, an examination can take up to 40 seconds to complete.<sup>27</sup> During this time, patient movement can cause motion artefacts. Children and adolescents may have a harder time understanding the need to be still during an examination, and the motion artefacts caused by this could impair diagnostic quality in CBCT images. Due to the in vitro design of *Paper II*, no artefacts (beam hardening, beam starvation effects, motion artefacts, metal artefacts) occurred, thus the results of *Paper II* should be interpreted with caution.

In many instances clinically, the CBCT unit FOV can be adjusted to obtain a volume of the area of interest. The employed protocols for the CBCT devices used in *Paper I* and *II* utilised the smallest possible FOVs. Applying a larger FOV than necessary unavoidably increases the dose level, and there is potential for reducing dose by offering the possibility of smaller FOV options for impacted canines.<sup>99</sup>

The retrospective study design of *Paper III* has an inherent disadvantage in that standardization of the 2D image quality wasn't possible. Because of the lack of standardization, the diagnostic efficiency of 2D images might have been underestimated. A larger prospective study in which more standardised images are obtained, containing qualified intraoral radiographs using the parallax technique could improve the validity of the results.

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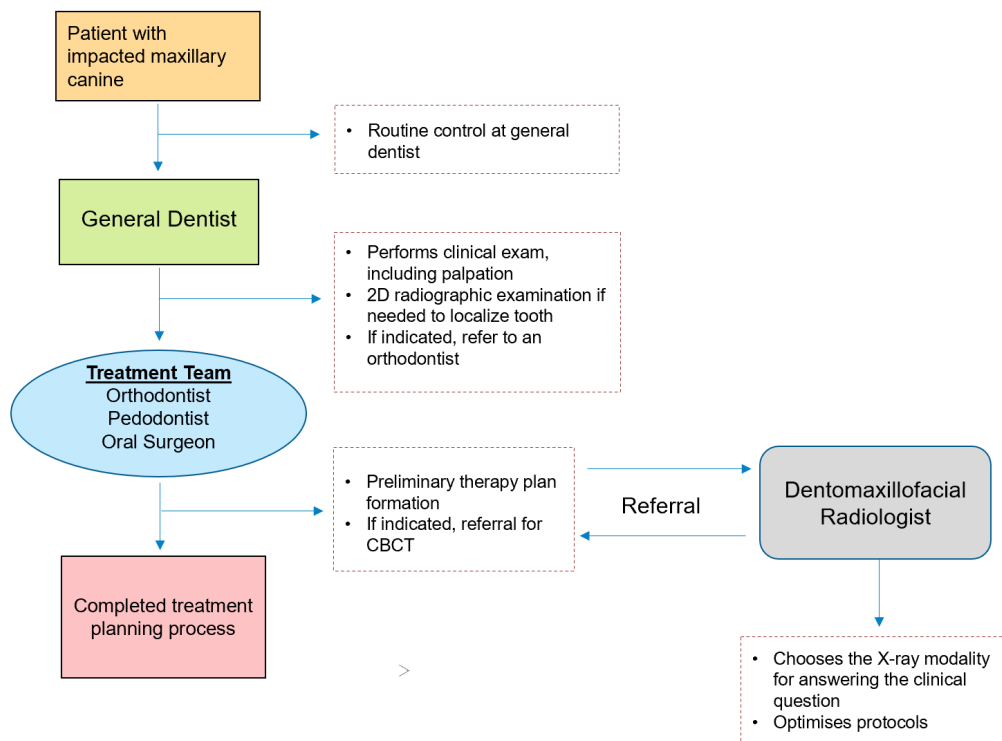
## 6.4 Clinical implications and future perspectives

Optimisation and justification are the most important principles in radiation protection, and their importance is emphasized when considering paediatric patients who are more radiosensitive than adults. New and emerging advanced 3D-imaging technologies often provide superior diagnostic information when compared to the conventional 2D radiographs that dentists have traditionally relied on. Still, 3D-imaging comes with increased radiation risks, and little is known about how additional 3D information impacts therapy planning and treatment outcome. A recent attempt to develop clinical guidelines for orthodontic radiology highlighted both a substantial lack of evidence in the field as well as a need for more research in this area.<sup>100</sup> This thesis provides data based on canine-induced lateral incisor resorption damage and how orthodontic specialists deal with the severity of the resorption when planning treatment, and the results of this thesis may assist clinicians in deciding when to best utilize CBCT technology while considering diagnostic benefits versus radiation risks.

Interdisciplinary therapy planning could increase the efficacy of the use of Cone Beam Computed Tomography (CBCT) with improved collaboration between dental specialties, resulting in clearer selection criteria for CBCT use. Currently, CBCT use should be restricted to when this modality is beneficial for clinicians to manage impacted maxillary canines.<sup>25</sup> Future prospective studies evaluating an interdisciplinary approach may provide valuable insights on areas of communication that can be improved between specialties that all play a part in impacted canine management.

In a clinical situation, each individual referral should be evaluated and the justification process should be done on the therapy-planning level. A Swedish study from 2020 found that 43% of the referrals for CBCT examinations in children and adolescents for assessing impacted canines were referred by general dentists, while orthodontists referred 26%.<sup>30</sup> We recommend that the member of the treatment team who has decided a preliminary therapy and who sends a referral to dentomaxillofacial radiologists be the same clinician to carry out the treatment (Figure 12). We also

recommend dentomaxillofacial radiologists to use low-dose optimised protocols.



**Fig. 12.** Treatment planning flowchart for impacted maxillary canines.

Currently, CBCT examinations are commonly applied for the clinical management of impacted maxillary canines, however, depending on the clinical situation of individual patients, the need for different diagnostic information may influence which dose protocol would be ideal.<sup>30, 101, 102</sup> The protocol needed for assessing a preliminary therapy plan of orthodontic force application may not be the same as the protocol needed for assessing preliminary therapy plans involving extractions.<sup>31</sup> While the patient dose burden can possibly be lowered by applying low-dose protocols that are indicated for different clinical situations, further clinical studies are necessary to investigate how such protocols are best applied. The recommended low-dose protocols from *Paper II* (ULDHD, ULD, LDHD) should be tested and adjusted in an in vivo design to take into consideration possible artefacts and positioning differences in

future prospective clinical studies. Future studies evaluating how often and why CBCT examinations need to be retaken may also provide meaningful information, from a dose-optimisation perspective.

*Paper III* did not take into consideration how the direction of orthodontic force applied to the impacted canine after surgical exposure or the canine's bone support might influence the results. These may be valuable markers to measure in future studies. Future studies investigating how the CBCT justification process presents in individual impacted canine cases, possibly in the form of a case series, may lift complex clinical situations where CBCT is justified.

This thesis considers how radiation protection principles apply to the specific task of impacted maxillary canine assessment, considering multiple aspects in the diagnostic efficacy ladder according to Fryback and Thornbury.<sup>67</sup> For manufacturers, we provide reference material to inspire continuing advancements in developing usable low-dose protocols, which will both benefit individual patients in question, and eventually enhance the cost-effectiveness of CBCT examinations at a societal level.

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## 7 SUMMARY OF RESULTS

### *Paper I*

- The effective dose from CBCT examinations ranged from 15 times to 140 times higher when compared to the effective dose from 2D examinations.
- CBCT should not be the first choice of imaging modality, rather CBCT scans should only be taken when deemed justified after 2D images could not provide necessary diagnostic information.

### *Paper II*

- When assessing the anterior maxilla using the Planmeca ProMax 3D Mid CBCT device, the ULDHD, ULD, and LDHD protocols may be recommended for clinical studies on assessing impacted maxillary canines. Compared to the standard protocol recommended by the manufacturer, these protocols provide comparable diagnostic information with a radiation dose of 23% to 39%.
- Planmeca AINO's noise reduction filter seems to have a positive effect on image quality when the exposure dose is low

### *Paper III*

- When assessing impacted maxillary canines, performing CBCT justification at the therapeutic thinking level increases the efficacy of CBCT, reinforcing a benefit-risk analysis and potentially limiting dose exposures.
- More than half of the CBCT exams performed based on diagnostic indications were not indicated when CBCT justifications were based on indications for treatment decision making or treatment execution.
- CBCT is indicated when preliminary treatment planning motivates further in-depth investigation of either root status or canine localization.

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## 8 CONCLUSIONS

- Employing CBCT low-dose protocols is an effective method for optimising patient dose burdens, however even the lowest optimised dose is higher than conventional 2D radiographs. Thus, the CBCT justification process should be considered carefully when selecting CBCT as an examination modality and CBCT should not be used as a first-hand alternative.
- Interdisciplinary therapy-planning may result in justified CBCT indications at the therapeutic thinking level, while simultaneously adhering to the ALARA principle of radiology, by limiting CBCT to clinical situations where information from CBCT is beneficial for the continuing treatment.
- Therapy-change due to significant root resorptions that affected extraction strategy is an important factor for requiring CBCT. In situations where therapy planning involving extraction strategy is important, CBCT is often justified.
- Diagnostic information from CBCT should be associated with the treatment plan. The referring clinician for CBCT should be involved in the entire treatment chain.
- To ensure CBCT is being selected with clear indications, a clear clinical question in combination with a preselected therapy choice is recommended for assessment of impacted maxillary canines.
- Even when optimised protocols have a drastically lower dose, CBCT examinations still expose patients to a higher dose than conventional 2D examinations. Additionally, not all clinical situations of impacted canines require CBCT examinations for treatment planning. The results of this thesis support adequate acquisition of conventional 2D images (periapical intraoral and panorama images) for preliminary assessment of the impacted canine's location and evaluation of suspected root resorptions prior to deciding whether CBCT is indicated.

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

Nils Kadesjö, Randi Lynds, Mats Nilsson, and Xie-Qi Shi.  
*Dentomaxillofac Radiol.* 2018;47(3):20170305.



## RESEARCH ARTICLE

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

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**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.

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**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%.<sup>1,2</sup> 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.<sup>3–7</sup> 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.<sup>5,8</sup> 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.<sup>3,5</sup> 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.<sup>9</sup> 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%.<sup>5,10</sup>

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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.<sup>9,11</sup> 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.<sup>5,7,12</sup>

A CBCT examination results in a higher radiation dose compared to panoramic and intraoral radiographs.<sup>13</sup> 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.<sup>14–16</sup> However, only a few studies have looked at the doses that children receive.<sup>17,18</sup> 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.<sup>19,20</sup> 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.

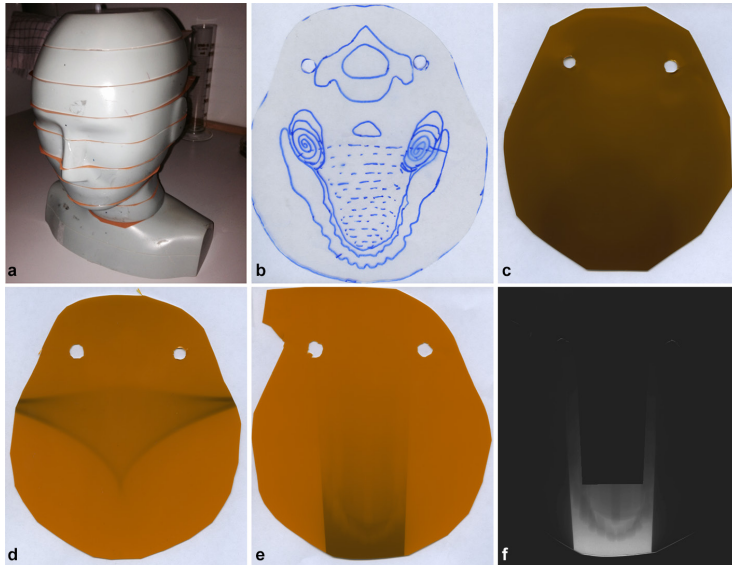
Measurements were taken using an ATOM-706-C paediatric 10-year-old anthropomorphic phantom (CIRS, Norfolk, VA). The phantom is comprised of tissue equivalent epoxy resins and divided into 25 mm thick slices. Within each slice is a 1.5 cm spaced grid of holes for the placement of TLDs. The top 10 slices 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 <sup>a</sup> (cm)	Voxelpixel size (mm)	DAP (mGycm <sup>2</sup> )
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.

<sup>a</sup>Size 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.<sup>21</sup> 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.<sup>21</sup> 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%.<sup>22</sup> 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%.<sup>23</sup> For the lymphatic nodes, the adult distribution from ICRP 110 was used: 6.3%.<sup>23</sup> 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](#).<sup>24</sup>

#### 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.<sup>25,26</sup> 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%.<sup>20</sup>

## 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 ( $\mu\text{Gy}$ ) for different radiographic examinations determined from TLD or film measurements

Organ	Mean organ dose ( $\mu\text{Gy}$ )					
	ProMax3D (TLD)	NewTom5G (TLD)	NewTom5G (film)	Panoramic (film)	Periapical lateral (film)	Periapical central (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  $\mu\text{Gy}$  and for periapical radiographs this corresponds to below 6  $\mu\text{Gy}$ .

The comparison between TLD and film measurements showed an excellent agreement in the resulting effective dose. Effective dose for a NewTom5G image was 172  $\mu\text{Sv}$  when calculated from the TLD measurements, compared to 166  $\mu\text{Sv}$  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**

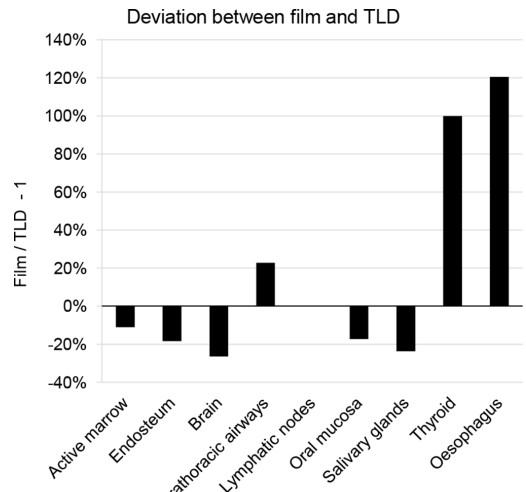
The investigated CBCT devices resulted in an examination with a much higher effective dose than that from a periapical or a panoramic X-ray examination. The specific extent of the total dose increase depends on the patient’s dental status, and the resulting choice of periapical and panoramic radiographs 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 ( $\mu\text{Sv}$ ) for each of the radiographic images, with effective dose for NewTom5G calculated both from TLD measurements and film measurements

Type of examination	Effective Dose ( $\mu\text{Sv}$ )
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.<sup>4,5,27</sup> However, there is no consensus whether this increased detection rate affects the treatment plan or not. Some studies found significant changes.<sup>5,7</sup> Others found no significant changes.<sup>27,28</sup> 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.<sup>12</sup> 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.

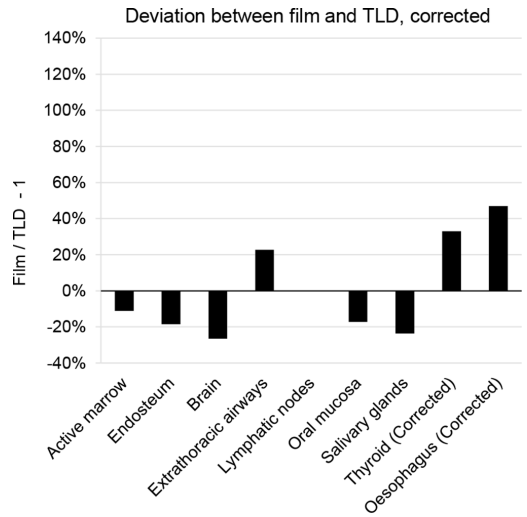
An accurate diagnosis based on proper clinical and radiographic evaluation is critical for the successful treatment of tooth impaction. When conventional intraoral radiography does not supply adequate information for therapeutic planning, a localized CBCT is indicated.<sup>9</sup> In this case, adequate 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.<sup>29</sup> 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  $4 \times 4$  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 mGycm<sup>2</sup>, 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.<sup>14–16</sup> An alternative method, using self-developing radiographic film, has also been used more recently.<sup>19,20,30</sup> 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.<sup>19</sup> 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.<sup>20</sup> 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.<sup>16</sup> 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.<sup>16,31</sup> Similar practice have been used for child phantoms.<sup>17,18</sup> 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  $\mu$ Sv and 5.1  $\mu$ Sv respectively for Promax3D, 94  $\mu$ Sv and 8.6  $\mu$ Sv respectively for NewTom5G (TLD), 4.7  $\mu$ Sv and 0.43  $\mu$ 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.<sup>16</sup>

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.<sup>24,32</sup> 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.<sup>17,18</sup> 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”.<sup>33</sup> There are available cancer-risk data, such as the United States Environmental Protection Agency “Blue Book”.<sup>34</sup> 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.

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**Image quality assessment of low-dose protocols in cone beam computed tomography of the anterior maxilla**

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II







## Image quality assessment of low-dose protocols in cone beam computed tomography of the anterior maxilla

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**Objectives.** To evaluate overall image quality and visibility of anatomic structures on low-dose cone beam computed tomography (CBCT) scans and the effect of a noise reduction filter for assessment of the anterior maxilla.

**Methods.** We obtained 48 CBCT volumes on 8 skull-phantoms using 6 protocols: 2 clinical default protocols [standard definition (SD) and high definition (HD)] and 4 low-dose protocols, 2 with a noise reduction filter [ultra-low-dose with high definition (ULDHD) and ultra-low-dose (ULD)] and 2 without [low-dose with high definition (LDHD) and low-dose (LD)]. Overall image quality and visibility of 8 anatomic structures were assessed by 5 observers and statistically analyzed using the Wilcoxon signed rank test. Intra- and interobserver agreement was measured using Cohen's weighted kappa.

**Results.** HD provided higher overall image quality than diagnostically required; LD scored lower than diagnostically acceptable. ULDHD, ULD, and LDHD were acceptable. For anatomic structures, ULDHD and ULD were acceptable. LDHD and LD showed significantly inferior visibility for 1 and 4 structures, respectively. Mean values of intra- and interobserver agreement were 0.395 to 0.547 and 0.350 to 0.370, respectively.

**Conclusions.** ULDHD, ULD, and LDHD may be recommended for assessment of impacted maxillary canines. The noise reduction filter affects image quality positively only at low exposure. (Oral Surg Oral Med Oral Pathol Oral Radiol 2022;133:483–491)

Obtaining two-dimensional (2D) radiographic images is common in dentistry when assessing the location of impacted canines, their relation to surrounding anatomic structures, and possible resorption of neighboring teeth.<sup>1-3</sup> When these images cannot provide enough diagnostic information for further treatment planning, current European guidelines recommend supplementing them with a localized small field of view (FOV) cone beam computed tomography (CBCT) volume.<sup>4-6</sup> The most common reason for obtaining a CBCT of the anterior maxillary region in adolescents is to assess impacted maxillary canines and their surrounding structures.<sup>7,8</sup> A missed diagnosis or delayed treatment results in 48% of

patients developing root resorption of permanent adjacent incisors, which then leads to further and often complicated orthodontic, surgical, and prosthetic treatments.<sup>9-11</sup>

Although the acquisition of three-dimensional (3D) CBCT volumes is rapidly increasing in popularity, the increased radiation-associated risks that CBCT entails warrant attention, especially regarding pediatric patients who have at least a three times greater risk for developing cancer from radiation exposure than adults.<sup>6,12,13</sup> The association between radiation exposure and cancer risk is important, and the significance of this risk is made more problematic when considering that the effects of radiation can appear earlier in the life span of young patients.<sup>14-18</sup> A recent dosimetry study of a 10-year-old anthropomorphic child phantom showed that the estimated dose burden for CBCT is 15 to 140 times higher compared with 2 intraoral radiographs, implying an increased risk of children developing radiation-induced cancer later in life.<sup>19</sup> Another study suggests that, even when the same imaging protocols are used, a 10-year-old receives a 30% higher effective dose from a dental CBCT examination than an adolescent would receive.<sup>20</sup> In response to the need to optimize pediatric dental X-ray examinations, the DIMITRA (Dentomaxillofacial paediatric imaging: an investigation toward low-dose radiation induced risks) research group has expanded upon the previously accepted “as low as reasonably achievable” (ALARA) and “as low as diagnostically acceptable” (ALADA) principles in radiology by recommending the use of exposure doses that are as low as diagnostically acceptable, indication-oriented, and patient-specific (ALADAIP).<sup>21-23</sup> The ALADAIP principle

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addresses the importance of conducting radiographic examinations in terms of maintaining diagnostically acceptable image quality for the individual patient's specific task while at the same time carefully applying imaging protocols with the lowest possible dose needed to maintain necessary image quality.

From a clinical point of view, a protocol can be optimized individually by adjusting the kilovolts (kV), milliampere-seconds (mAs), voxel size ( $\mu\text{m}$ ), and number of frames captured when obtaining a scan and by limiting the FOV so that radiation exposure is confined to the anatomic area that is relevant for the diagnostic task in question. Optimized protocols have been investigated for other diagnostic purposes and are reportedly effective in reducing patient dose.<sup>24-26</sup> A study that examined optimized protocols for assessing the lamina dura found that an ultra-low-dose protocol with HD did not differ statistically from the 4 top-ranking protocols tested, implying that even fine structures usually requiring HD can be visualized with lower dose exposures.<sup>27</sup> Some researchers believe that a high-definition CBCT image is needed for diagnosing impacted canines to identify small but clinically relevant tissue or morphologic changes in the tooth and surrounding structures.<sup>23</sup> Low-dose CBCT protocols have also been suggested.<sup>28,29</sup> However, only 1 study, using 1 phantom for protocol testing, has evaluated the image quality of scanning protocols intended for maxillary canine impaction. Although high-dose protocols produce subjectively appealing images, the cost of extra radiation to the patient is not justified if low-dose images that are diagnostically sufficient could potentially limit exposure dose.<sup>30</sup>

Optimization of exposure, such as by developing low-dose protocols, is an effective strategy to reduce patient dose during radiographic examinations. Still, the dramatically reduced exposure inevitably comes with a reduced signal-to-noise ratio (SNR) in the resultant images.<sup>28</sup> Planmeca Oy offers ultra-low-dose protocols with reduced mAs combined with a lower number of pulsed exposures that introduce a reduced SNR in the resulting image. To compensate for the noise caused by low mAs and fewer projections, a noise reduction filter (the Adaptive Image Noise Optimiser [AINO] filter, Planmeca Oy, Helsinki, Finland) is automatically applied to these ultra-low-dose (ULD) and ultra-low-dose with high definition (ULDHD) protocols.

The aims of the present study were twofold: (1) to compare the subjective evaluation of overall image quality of CBCT scans designed to depict impacted maxillary canines exposed with 6 protocols using combinations of exposure parameters and the AINO noise reduction algorithm, and (2) to compare the visualization of 8 anatomic structures as depicted with the 6 protocols.

## MATERIAL AND METHODS

### Experimental design

Eight dry human skulls, previously used as teaching materials at the Karolinska Institute, Huddinge, Sweden, were employed as test phantoms. Because the origins of the specimens were untraceable, the regional ethics review boards in Stockholm (Dnr: 2007/1288-31/2) and in Bergen (Dnr: 161998) concluded that there were no potentially conflicting ethical aspects in the present study.

The dry skulls were used to construct test phantoms as described in an earlier study by Liljeholm et al.<sup>24</sup> Occlusion for each skull was stabilized using dental impression material, both between the maxillary and mandibular teeth as well as between the temporomandibular joint fossa and the condyle bilaterally. Soft tissue was simulated by placing each skull into a clear close-fitted and water-filled plastic bag. The bag was then placed into a cylindrical container made of 5.0-mm thick acrylic, with a diameter of 20 cm. A 4.0 × 6.0-cm plexiglass cylinder was placed underneath each skull to simulate the atlas vertebra and provide balance for each specimen. Air-filled examination gloves were also used as additional stability for each skull's position during exposure (Figure 1).

### CBCT examination

Six CBCT scans were obtained for each of the 8 skulls using the Planmeca ProMax 3D Mid system. The scanning protocols employed in the project consisted of 4 of the existing protocols suggested by the manufacturer, as follows: a standard definition protocol (SD), which is the clinical default protocol for canine impaction; a high definition protocol (HD) usually used for detecting fine details, such as endodontics-related diagnostic tasks; an ultra-low-dose protocol with high definition (ULDHD); and an ultra-low-dose protocol (ULD). Both the ULDHD and the ULD protocols use Planmeca's AINO noise reduction filter. The HD scans had a voxel size of 150  $\mu\text{m}$ , and protocols without HD had a voxel size of 200  $\mu\text{m}$ . Additionally, we tested a low-dose protocol with high definition (LDHD) and a low-dose protocol (LD). These 2 protocols were self-developed and aimed at producing dose levels equivalent to the ULDHD and ULD protocols, respectively, but without the AINO noise reduction algorithm (Table 1). All CBCT exposures had a 4.0 × 5.0-cm FOV obtained with a single 210-degree rotation. Representative axial sections from each of the 6 protocols are illustrated in Figure 2.

### Image evaluation

The 48 volumes were randomly coded using Microsoft Excel Worksheet (Redmond, WA, USA) and organized in Romexis (version 3.8.3.R 2014-12-17, Planmeca).

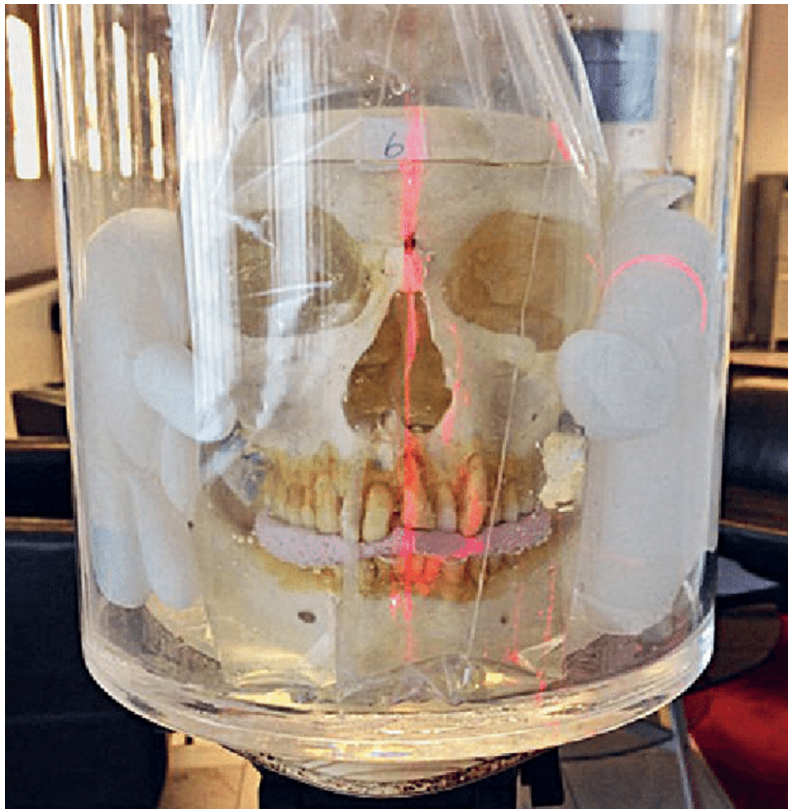


Fig. 1. A skull phantom as prepared for acquisition of the CBCT scans. (Reprinted with permission of the publisher from Liljeholm et al. 2017.)

**Table I.** Detailed information regarding the exposure protocols

Protocol	Type	Definition	kV	mAs	Voxel size ( $\mu\text{m}$ )	Frames	Nominal DAP ( $\text{mGycm}^2$ )	Dose fraction of the SD (%)
SD*	Standard	Normal	90	96	200	400	329	100%
HD*	Standard	HD	90	150	150	500	514	156%
ULDHD*	ULD	HD	90	36	150	500	122	37%
ULD*	ULD	Normal	90	23	200	400	77	23%
LDHD†	Low-dose	HD	90	38	150	500	129	39%
LD†	Low-dose	Normal	90	22	200	400	74	22%

kV, kilovolts; mAs, milliamperere-seconds; DAP, dose area product; SD, standard deviation; HD, high definition; ULD, ultra-low-dose; LD, low-dose.

\*Manufacturer's default protocols: Standard definition (SD): current clinical default for impacted canine examination, High definition (HD), Ultra-low-dose with high definition (ULDHD), Ultra-low-dose (ULD). Both the ULDHD and the ULD protocols use the Planmeca Adaptive Image Noise Optimiser (AINO) noise reduction filter.

†Self-developed protocols. Low-dose with high definition (LDHD) and low-dose (LD) were established to produce dose levels equivalent to the ULDHD and ULD, respectively, but without the quality enhancement AINO algorithm.

Each CBCT data set was assessed independently by 5 specialists in dentomaxillofacial radiology. The observers all had at least 3 years of experience, with a range of 3 to more than 10 years, in the interpretation of CBCT scans. Each observer had prior experience working with Romexis clinically. The observers were

blinded to the exposure protocols and phantom numbers during the image assessments.

All observers examined the images under identical viewing conditions consisting of a dimly lit room and a 19-inch screen with  $1280 \times 1024$  definition (Eizo Flexscan, Model MX190, EIZO Nanao Corporation,

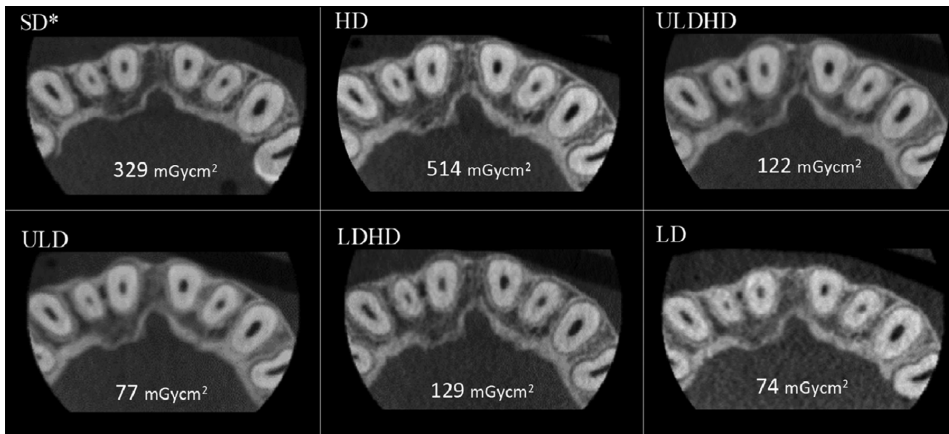


Fig. 2. CBCT axial sections from the same phantom captured using the 6 examination protocols, with the corresponding dose area product (DAP) values. \*SD, standard definition; HD, high definition; ULDHD, ultra-low-dose with high definition; ULD, ultra-low-dose; LDHD, low-dose with high definition; LD, low-dose. \*Current clinical default setting with standard definition (SD).

Hakui, Ishikawa, Japan). The screen display was adjusted to the Digital Imaging and Communications in Medicine (DICOM) mode enabled by the monitor settings, in which the gray-scale display was calibrated as described by Barten.<sup>31</sup> Image manipulation was allowed, enabling the observers to adjust the grey level, contrast, and multiplanar reconstruction according to their individual preferences.

**Overall image quality and visibility of anatomic structures**

The CBCT data sets were evaluated in terms of the overall subjective impression of the quality of the CBCT images of the anterior maxilla and the detectability of anatomic structures. Detailed instructions about the evaluation criteria, including how to rate the overall image quality and the visibility of the structures, were given to all observers.

Image quality was defined as the ability of the image to answer diagnostic questions in the clinical situation of impacted maxillary canines. The overall image quality for each of the 48 CBCT volumes was individually ranked according to an ordinal scale of 1 to 4, in which 1 was poor, 2 was questionable, 3 was good (diagnostically acceptable), and 4 was excellent.

The anatomic structures included a range of radiographically visible landmarks in the anterior maxillary region that commonly provide vital diagnostic information for future orthodontic treatment regarding the interpretation of the canine position as well as possible canine-induced root resorption (Table II). The following structures were assessed: (1) the intermaxillary suture; (2) the incisive foramen and canal(s); (3) the cortical bone of the buccal/palatal surface of the

maxilla; (4) the trabecular bone pattern (spongiosa); (5) the distinction of the grey level difference in enamel, dentin, and pulp; (6) the lamina dura; (7) the periodontal ligament space; and (8) the distinction of the root apex shape. The structures were assessed in terms of their visibility according to an ordinal scale of 1 to 4, in which 1 indicated that the structure was not visible, 2 indicated questionable visibility (diffuse, noisy), 3 indicated that the structure was visible (diagnostically acceptable for the task of assessing impacted maxillary canines), and 4 indicated that the structure was distinctly visible. The most common score value of all observers' answers was considered representative of the overall image quality and the level of visibility for each anatomic structure in question and used for data analysis.

Twelve CBCT scans (from 2 of the 8 skulls) were reassessed by all 5 observers with a time lag of at least 3 weeks. This process provided reproducibility data for 25% of all CBCT images.

**Statistical analyses**

The statistical analysis was performed using SPSS (IBM SPSS Statistics, version 27, IBM Corp, Armonk, NY, USA).

The one-sample Wilcoxon signed rank test was applied to determine whether the median of overall image quality and landmark visibility for each of the protocols was significantly different from a hypothetical median, "3," representing the cut-off for diagnostic acceptability according to our ordinal scale. The null hypothesis was that the overall image quality and visibility of each structure were at a diagnostically acceptable level (score 3) for the task of assessing anterior

**Table II.** Anatomic structures examined in the current study and their definitions

Structures	Definition
Intermaxillary suture	Thin radiolucent line interproximal to the central incisors and inferior to the anterior nasal spine, forming the midline of the premaxilla.
Incisive foramen and canal(s)	Ovoid radiolucency in the palate directly posterior to the central incisors (foramen) with radiopaque lateral borders around radiolucencies extending from the anterior floor of the nasal fossae to the anterior maxillary midline (canals).
Cortical bone	Radiopaque borders located on the buccal and palatal surfaces of the alveolar bone.
Trabecular bone pattern (spongiosa)	Cancellous bone located between the cortical plates, visualized as thin radiopaque trabeculae traversing many small radiolucent cavities.
Gray level difference in enamel, dentin, and pulp	Clear distinction between the gray levels of enamel and dentin at the dentinoenamel junction and between dentin and pulp.
Lamina dura	Thin radiopaque line located in the alveolar bone surrounding the roots of the teeth.
Periodontal ligament space	The radiolucent space located between the tooth root and the lamina dura.
Root apex shape	Clear distinction of the shape and contours of the root apices.

maxillary structures, including impacted maxillary canines, for all 6 scanning protocols. The significance level was set at  $P = .05$ .

Intra- and interobserver agreement was established using Cohen’s weighted kappa statistics. The outcome was interpreted according to the Landis and Koch scale for observer agreement in assessing categorical data.<sup>32</sup> Kappa scores are interpreted in this scale as almost perfect (0.81-1.0), substantial (0.61-0.80), moderate (0.41-0.60), fair (0.21-0.40), and poor (0.0-0.20).

**RESULTS**

Subjective overall image quality differences were seen between some of the examination protocols (Figure 3). The protocols that ranked highest for overall image quality, HD and SD, were the 2 protocols that also had the highest radiation burden for the patient, with HD at 156% of the dose for the reference standard dose (100%), as shown in Table I. The AINO noise reduction filter, applied to the ULDHD and ULD protocols, seemed to be needed only when the exposure was reduced dramatically, such as with the LD protocol.

The overall image quality and visibility of the 8 anatomic structures based on the 5 observers’ scores were measured as observed median values for each scanning protocol, using the one-sample Wilcoxon signed rank test (Table III). For the overall image quality, the results of 2 scanning protocols allowed rejection of the null hypothesis; the HD protocol had a significantly higher median value ( $P = .014$ ), and the LD protocol had a significantly lower median value ( $P = .034$ ) than the hypothetical diagnostically acceptable value of “3.” The high score for HD required a much larger radiation exposure at 156% of the dose for the SD protocol. The LD protocol required 22% of the SD dose but with a significantly poorer outcome.

With regards to the visibility of anatomic structures, a number of structures had significantly higher medians than “3” (highlighted). Of these, the most

prominent protocol was HD with 6 of the 8 structures receiving significantly higher scores ( $P \leq .020$ ), indicating that the image quality of HD is unnecessarily superior to what is diagnostically needed (Table III). The LDHD protocol had a significantly lower median value than “3” for the precision of identifying the intermaxillary suture ( $P = .020$ ). The LD protocol showed a significantly inferior visibility than the standard in recognizing the intermaxillary suture, trabecular bone pattern, lamina dura, and periodontal ligament space ( $P \leq .017$ ). These findings allow rejection of the null hypothesis regarding visibility of the structures for the LDHD and LD protocols.

Based on all five observers, intraobserver agreement of overall image quality ranged from 0.286 to 0.471 (fair to moderate) with a mean of 0.395, and intraobserver agreement regarding the anatomic structure visibility ranged from 0.485 to 0.66 (moderate to substantial) with a mean of 0.547.<sup>32</sup> Pairwise interobserver agreement based on the 5 observers regarding overall image quality ranged from 0.167 to 0.513 (poor to moderate) with a mean of 0.350, and interobserver agreement regarding anatomic structure visibility ranged from 0.135 to 0.537 (poor to moderate) with a mean of 0.370.<sup>32</sup>

**DISCUSSION**

Our results suggest that the overall image quality was at a diagnostically acceptable level for the defined diagnostic task using the following 4 protocols: SD, ULDHD, ULD, and LDHD. HD was rejected due to unnecessarily high image quality, and LD was rejected for producing unacceptably poor image quality.

A compounding problem when trying to determine a radiologist’s preference is that a visually pleasing image could subjectively be seen as superior even though an image with lower definition could suffice for accurate interpretation.<sup>33</sup> High-dose exposure protocols with fine spatial definition may be necessary for

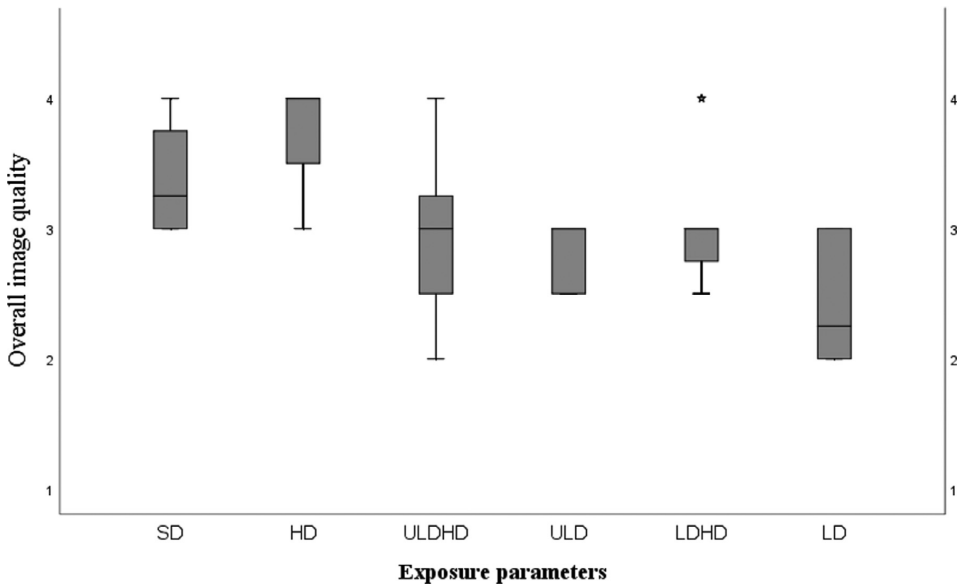


Fig. 3. Overall image quality in relation to exposure protocols. SD, standard definition; HD, high definition; ULHD, ultra-low-dose with high definition; ULD, ultra-low-dose; LDHD, low-dose with high definition; LD, low-dose. The top of the box represents the 75<sup>th</sup> percentile; the bottom of the box represents the 25<sup>th</sup> percentile, and the middle line represents the median. The whiskers extend from minimum to maximum values, excluding outliers or extreme values. The star beyond the whisker represents an outlier.

**Table III.** One-sample Wilcoxon signed rank test for exposure protocols

	<i>SD median (significance*†)</i>	<i>HD median (significance*†)</i>	<i>ULDHD median (significance*†)</i>	<i>ULD median (significance*†)</i>	<i>LDHD median (significance*†)</i>	<i>LD median (significance*†)</i>
Overall image quality	3.25 (0.063)	4.00 ( <b>0.014</b> )	3.00 (0.783)	3.00 (1.000)	3.00 (0.083)	<u>2.25 (0.034)</u>
Intermaxillary suture	3.00 (0.705)	3.25 (0.098)	2.00 (0.086)	2.00 (0.079)	<u>2.00 (0.020)</u>	<u>2.00 (0.017)</u>
Trabecular bone pattern	3.25 (0.258)	4.00 ( <b>0.019</b> )	3.00 (0.748)	2.00 (0.067)	3.00 (0.102)	<u>2.00 (0.011)</u>
Cortical bone	3.50 ( <b>0.015</b> )	4.00 ( <b>0.007</b> )	3.50 ( <b>0.038</b> )	3.75 (0.052)	3.00 (0.257)	3.00 (0.257)
Incisive foramen and canal(s)	4.00 ( <b>0.005</b> )	4.00 ( <b>0.005</b> )	4.00 ( <b>0.014</b> )	4.00 ( <b>0.025</b> )	3.00 (0.317)	3.00 (0.083)
Gray level difference in enamel, dentin, and pulp	3.50 ( <b>0.046</b> )	4.00 ( <b>0.008</b> )	3.50 ( <b>0.023</b> )	3.50 ( <b>0.034</b> )	3.50 ( <b>0.034</b> )	3.00 (0.157)
Lamina dura	3.00 (1.000)	3.75 (0.052)	3.00 (0.458)	2.75 (0.098)	2.75 (0.129)	<u>2.00 (0.014)</u>
Periodontal ligament	3.25 (0.234)	4.00 ( <b>0.020</b> )	3.25 (0.408)	2.00 (0.058)	2.75 (0.059)	<u>2.00 (0.014)</u>
Root apex shape	4.00 ( <b>0.025</b> )	4.00 ( <b>0.005</b> )	3.25 (0.059)	3.00 (0.180)	3.00 (0.180)	3.00 (0.655)

One-sample Wilcoxon signed rank test for overall image quality and the visibility of the 8 anatomic structures using the hypothetical median of “3” (diagnostically acceptable) for the exposure protocols. The observed medians and their *P* values are listed for each protocol. Data underlined indicates the observed medians that are significantly lower than 3, whereas highlighted data indicates the observed medians that are significantly higher than 3.

SD, standard definition; HD, high definition; ULHD, ultra-low-dose high definition; ULD, ultra-low-dose; LDHD, low-dose high definition; LD, low-dose.

\*The significance level is *P* = .05.

†Asymptotic significance is displayed.

evaluating impacted canines. The HD of these protocols provides a reliable assessment of key anatomic structures in the anterior maxilla, which is paramount for diagnostic and treatment purposes.<sup>23</sup> In the present study, the HD protocol was overqualified when considering that the significantly higher overall quality score came with a greater radiation burden to the patient. Both HD and SD could be replaced by ULDHD, ULD, or LDHD protocols, which all provided diagnostically acceptable image quality for impacted canines while simultaneously reducing the dose for this group of patients by 63%, 77%, and 61%, respectively, compared with the SD protocol. These 3 LD protocols demonstrated the best balance between image quality and radiation burden for diagnosing anatomic structures in the anterior maxilla and are therefore suitable for CBCT examinations for assessing impacted maxillary canines. This finding is in line with a previous study by Rivas et al.,<sup>28</sup> in which a 50% dose reduction could be reached through dose optimization.

Within the scope of the present study, the dose area product (DAP) was used as a feasible way to determine the relative dose reduction between examination protocols. The kV, filtration, and FOV size and position were kept constant. Under these conditions, DAP and effective dose are directly proportional to each other. Thus, a 63% relative difference in DAP corresponded to a 63% relative difference in effective dose. Note that DAP cannot be directly used to compare radiation doses between examinations of different anatomic locations and FOV size or with different X-ray energies (determined by kV and filtration). Different X-ray devices could also have different irradiation geometries, such as the angle of rotation. Comparing DAP under any of those conditions introduces potentially large errors, making effective dose a more valuable tool.<sup>34</sup>

Of the ULDHD, ULD, and LDHD protocols, LDHD stood out as significantly poorer for visualizing the intermaxillary suture ( $P = .020$ ). A plausible reason for this finding is the large variation in the suture among adults. It is difficult to detect when ossification occurs during development, especially when the CBCT voxel size is larger than half of the suture size. The intermaxillary suture has the most delicate details of the anatomic structures that were evaluated, so it was expected to be difficult to visualize. However, impacted canine assessments and their related diagnostic tasks rarely require clear visibility of the intermaxillary suture, and the visibility of this structure may only be indicated in a few select cases.

The median values of structure visibility generally decreased as the radiation dose decreased (Tables I and III). The LD protocol stands out as insufficient because

the observed median values were significantly lower than “3” in detection of the intermaxillary suture, the trabecular bone pattern, the lamina dura, and the periodontal ligament space. Inferior image quality in terms of structure visibility was not observed using the ULD protocol, which had a comparable dose level to the LD protocol (77 mGycm<sup>2</sup> for ULD vs 74 mGycm<sup>2</sup> for LD), indicating the positive effect of the AINO noise reduction filter. Noise within a certain range does not degrade diagnostic performance, as previous studies have shown.<sup>35-37</sup> However, when the exposure is dramatically reduced, the resultant image can have a noisy, distracting visual appearance, and the visibility of subtle anatomic structures may be affected, such as with the LD protocol. In this case, a noise reduction filter might be necessary to compensate for the reduced SNR.

If visualization of fine structures such as the intermaxillary suture, trabecular bone pattern, lamina dura, or periodontal ligament space is not essential for the patient's clinical situation, the other structures of interest for impacted canines can be seen with the LD protocol.

When deciding on the appropriate method for radiographic analysis in Sweden, the dentomaxillofacial radiologist is responsible for the choice of the applied modality and exposure settings that are deemed necessary for the diagnostic task. Internationally, orthodontists in many instances make this decision. However, there is a lack of scientific evidence illustrating which CBCT dose protocol should be used when examining impacted maxillary canines. To add to the challenge of selecting and optimizing protocols, different clinical situations require patient-specific diagnostic information that is dependent on what the clinician requires for therapeutic planning, even for the same diagnostic task. For example, patients with impacted maxillary canines may require different protocols depending on whether the tooth will be treated with orthodontic force or extracted.<sup>23</sup> When faced with a diagnostic task that requires clearly visible fine details for certain structures, a protocol with a higher exposure and fine spatial definition is needed.

From a clinical point of view, decision making in treating impacted canines can be influenced by information about the position of the canine and the location of canine-induced root resorptions.<sup>5,38</sup> Currently, the management of canine impaction commonly includes acquiring diagnostic information obtained from CBCT, although little is known about how LD protocols could influence the choice of therapy or treatment outcome.<sup>7,8,39</sup> Further clinical studies are needed to identify how the application of LD protocols can be selected and applied, based on information from the present study on the visibility of the anatomic structures.



Intraobserver agreement in this study ranged from fair to substantial. The LD protocols were quite similar to each other, and low intraobserver agreement could be explained by the subtle differences between protocols. Interobserver agreement regarding subjective preference varied greatly between viewers, with weighted kappa values ranging from 0.167 to 0.513, indicating that the radiologists had differing subjective preferences. In the field of radiology, subjective preference in image quality differs depending on the individual who is interpreting the images. To account for this difference, we used the most common score value of the observer's answers to represent the average demand on image quality. Similar levels of agreement can be seen in a previous dose optimization study, although these results are not directly comparable to the current investigation.<sup>24</sup> Our results regarding interobserver agreement reflect the current clinical situation of different subjective preferences on image quality among dentomaxillofacial radiologists. However, observers were given detailed verbal instructions about the evaluation criteria, and no practical calibration was performed using extra CBCT volumes because we used all the skulls that we had available for the study. In the present investigation, most of the observers were not used to viewing LD CBCT images. Therefore, we expect that after more perceptual training and precalibration of observers, the intra- and interobserver agreement may be increased in future studies.

Based on these results, future similar studies on image quality assessment, assuming that a significant difference of 0.5 with a standard deviation of 0.4 is expected using a 4-rank scale, will require a minimum sample size of 8 phantoms. Our measurements resulted in a standard deviation of approximately 0.4. A limitation with our in vitro design was that none of the 8 specimens had canine impaction. The ideal study design would be based on phantoms that are age-appropriate with impacted canines, but such phantoms are difficult to collect. Previous research performed in vivo on patients with impacted canines have evaluated diagnostic accuracy, but to our knowledge none have focused on image quality. Performing this study and applying 6 different protocols in vivo is not ethically practical due to the radiation burden to the patients.

This study tested image quality using dry skull phantoms, and the images for each protocol were standardized in terms of positioning and lack of motion. This precluded a comparison of images with motion artifacts. Our results should be interpreted with caution because, with an in vivo design, we would expect to see artifacts due to the canine overlapping the roots of adjacent teeth, beam hardening/beam starvation effects, motion artifacts, and metal artifacts. Testing and adjusting the proposed ULDD, ULD, and LDHD

protocols in a clinical situation should be evaluated in future prospective clinical studies.

## CONCLUSIONS

For the CBCT unit Planmeca ProMax 3D Mid, the ULDD, ULD, and LDHD protocols may be recommended for clinical studies on assessing impacted maxillary canines because these protocols provide comparable diagnostic information with a radiation dose of 23% to 39% of the standard protocol recommended by the manufacturer. Planmeca AINO's noise reduction filter seems to have a positive effect on image quality when the exposure dose is low.

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## PRESENTATION

Preliminary results of this study were presented at the Odontologisk Riksstämman, a national dental conference in Stockholm, Sweden in November 2020 in the form of an oral presentation.

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