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2022-11

Katlapa , A , Kaartinen , S M , Koivisto , J H & Matikka , H 2022 , ' Radiation exposure to fetus from extremity CBCT examinations ' , European Journal of Radiology , vol. 156 , 110548 . https://doi.org/10.1016/j.ejrad.2022.110548

http://hdl.handle.net/10138/351959
https://doi.org/10.1016/j.ejrad.2022.110548

European Journal of Radiology 156 (2022) 110548

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Radiation exposure to fetus from extremity CBCT examinations

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ARTICLE INFO

Keywords:
Cone-beam computed tomography
Fetal dose
Fetal dose optimization

ABSTRACT

Purpose: To evaluate fetal doses from extremity CBCT examinations at different stages of pregnancy and to investigate different methods of fetal dose optimization.
Method: Fetal doses were measured in an anthropomorphic phantom for two CBCT examination protocols – knee and elbow. The measurements were made at three different heights representing the three trimesters during pregnancy and three different depths in the phantom. The effect of soft tissue layer, tube voltage, add-on device shield and body angulation on fetal dose were investigated.
Results: The fetal doses in clinical examination protocols were in the range of 3.4 to 6.0 μGy during knee examinations and 2.9 to 7.7 μGy during elbow examinations depending on the depth of the fetus and the stage of pregnancy. A soft tissue layer representing variative body composition above abdomen region decreased the fetal dose up to 19 % in knee and up to 21 % in elbow examinations. Using lower tube voltage decreased the fetal doses up to 45 % (knee) and 51 % (elbow). An add-on device shield decreased the fetal doses up to 91 % (knee) and up to 75 % (elbow). Turning the body away from the device bore reduced the fetal doses up to 62 %. The conversion factor to convert an entrance surface dose to the fetal dose ranged from 0.4 to 0.6.
Conclusions: The fetal doses from CBCT examinations of extremities are low and do not produce a concern about radiation detriment to the fetus. The most efficient way found to reduce the fetal dose was to use the add-on device shielding.

1. Introduction

Cone-beam computerized tomography (CBCT) has been implemented to routine use in clinical radiology mainly during the last two decades. Initially it was meant for oral and maxillofacial examinations [1,2], but shortly after implementation applications for musculoskeletal imaging – typically for wrist, ankle, knee, elbow and foot – were also developed [3,4]. CBCT uses a conical X-ray beam which rotates around the patient and allows obtaining 3D images. It has been commonly characterised as a widely available low-cost examination with a relatively low radiation dose [3–5]. Doses in musculoskeletal imaging have been shown to be lower with CBCT than with conventional computed tomography (CT) [5,6]. The effective dose for a knee examination has been estimated to be 12.6 μSv for CBCT in comparison to 27–48 μSv for an equivalent CT scan [5]. In another study, the effective dose for an elbow examination was estimated to be in the range from 2.0 to 6.7 μSv for a CBCT scan and 37.4 μSv for CT [6]. From a clinical point of view, CBCT has been proved as a useful imaging modality for many clinical applications of the musculoskeletal system, showing the visibility of bone details and some soft tissues [4]. Also, advantages of CBCT over such common techniques as conventional radiography, CT, or magnetic resonance imaging have been widely reported [7–14]. CBCT has been shown to detect more accurately certain kind of fractures therefore preventing longer immobilization and restrictions of activities. Moreover, CBCT gives possibilities to assess extremities under weight-bearing conditions and can have advantages in image quality in the presence of metal objects.

In the CBCT imaging of the musculoskeletal system radiation-

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https://doi.org/10.1016/j.ejrad.2022.110548
Received 16 May 2022; Received in revised form 12 September 2022; Accepted 26 September 2022
Available online 30 September 2022

sensitive organs, other than bone marrow, are typically not in the primary beam. It has been estimated that irradiated fraction of bone marrow in knee examinations is approximately 1.9 % [5] and in elbow region 1.0 % [6] of the total bone marrow mass. Thus, the focus in radiation protection is mainly in protecting other sensitive organs from the scattered radiation. In a study by Matikka et al. 2014 [15] different organ doses resulting from CBCT examination of an elbow were assessed. Their estimation for eye dose was up to 61.5 μGy; for parotid gland – up to 182.7 μGy; for breast – up to 438.3 μGy; for thyroid gland – up to 51.6 μGy. However, based on our thorough literature review the fetal doses from CBCT examinations of the musculoskeletal system have not been reported. An estimate of fetal doses in the range up to 6.9 μGy has been reported for dental CBCT examinations only [16]. Generally fetal doses from radiological examinations are estimated by measuring doses in anthropomorphic phantoms using metal–oxidesemiconductor field-effect transistor [17], thermoluminescent [18] or other [16] dosimeters, or using theoretical calculations [19] and Monte-Carlo simulations [20].

Special radiation protection of fetus during pregnancy has been emphasized internationally and also European Directive 2013/59/Euratom states that in case of pregnancy special attention must be given to the optimization of medical radiological procedure taking into account also the unborn child [21]. The directive has been implemented to national legislations of European Union countries including Finland [22]. These requirements emphasize the importance of knowing the factors that affect the fetal doses and the means for optimizing them.

The aim of this study was to evaluate fetal doses from CBCT examinations of knee and elbow for different stages of pregnancy. In addition, different methods of fetal dose optimization were investigated to discover how much the fetal doses can be reduced using clinically applicable practical means.

2. Materials and methods

2.1. CBCT device and exposure parameters

Fetal doses were measured for two CBCT examinations – knee and elbow. Knee and elbow examinations were chosen as they were considered to give the highest radiation dose to the fetus with the abdominal region of the mother being the closest to the device bore. The measurements were performed using a clinically established and rather widely used Planmed Verity® CBCT scanner (Planmed Oy, Helsinki, Finland) and an anthropomorphic phantom. The scanner is equipped with a 0.25 mm lead equivalent add-on radiation shield (Fig. 1) which can be attached to the scanner bore by magnetic fasteners and weighs approximately 1.6 kg. The fetal doses were measured both with and without the shield.

Three different examination protocols were used – clinically used protocol for an examination of a standard size patient (further – Clinical protocol); and protocols with the lowest and the highest kV available (further – Low kV protocol and High kV protocol accordingly) (Table 1). All the examinations were performed using a 0.4 mm resolution and 400 scanned projections with 20 ms pulse length, and a large field-of-view (10 cm length at isocenter).

2.2. Dosimeter

The fetal doses were measured as air kerma using a calibrated RaySafe Xi unit and Xi Survey Detector (Unfors RaySafe AB, Billdahl, Sweden) which is a solid state detector designed for measuring scattered radiation. Xi Survey Detector is suitable for the use in an energy range of 13 keV to 1.25 MeV, the minimum response time is 0.5 s and the cumulative dose range is 0 μGy to 9999 μGy with the maximum resolution of 0.001 μGy. The detector is presenting a constant (±10 %) response over front axial range of 150 degrees. However, the detector is unable to detect photons coming from the back of the detector. Based on detector specifications it was found suitable for the measurements of cumulative dose inside an anthropomorphic phantom and has also been used in other similar studies [16]. The repeatability of the measurements was pre-tested with the same setup and dose range conditions as used in actual measurements. Repeatability was found to be excellent – showing less than 1 % deviation - therefore in actual measurements each measurement was repeated one to three times (three times at least for every new measurement geometry and for doses that were less than 1 μGy).

Fig. 1. The Planmed Verity scanner with the shield.

Table 1
Exposure parameters for knee and elbow examination protocols. ($CTDI_{vol}$ – volumetric CT dose index; DLP - dose-length product).

	Tube voltage (kV)	Tube current (mA)	Scan time (s)	$CTDI_{vol}$* (mGy)	DLP (mGycm)
Knee examinations					
Clinical protocol	90	6.3	24.4	3.8	49.5
Low kV protocol	80	6.3	24.4	2.3	30.4
High kV protocol	96	6.3	24.4	4.9	63.4
Elbow examinations					
Clinical protocol	92	5.0	24.4	3.3	43.0
Low kV protocol	80	5.0	24.4	1.9	24.2
High kV protocol	96	5.0	24.4	3.9	50.3

* $CTDI_{vol}$ values were given and measured regularly by the manufacturer according to the IEC 60601–2-44–2016 standard.

2.3. Phantom and measurement geometry

Anthropomorphic phantoms were used to mimic mother's body - Alderson Rando™ Female ART-300 phantom (Radiology Support Devices Inc., Long Beach, CA, USA) was used to simulate woman's body and a custom-made anthropomorphic RANDO leg and arm phantoms (Radiation Analogue Dosimetry System; The Phantom Laboratory, Salem, NY, USA) were used for leg and arm.

The fetal dose measurements were conducted at three different heights inside the Alderson phantom representing the first (slice 30 of Alderson phantom), the second (slice 27), and the third (slice 22) trimester of pregnancy. The measurement heights were chosen to cover fetus position from the lowest (position of the uterus in the first weeks of pregnancy) to the highest (liver level in the last weeks of pregnancy) possible. For each height, the respective slice of Alderson phantom was taken out and replaced by wooden spacers on the back and a solid, homogeneous, soft tissue-equivalent (bolus) material (Civco Radiotherapy, Coralville, Iowa, USA) in the front and sides. Wooden spacers were used at the back of the phantom to provide the necessary gap between phantom slices to insert the dosimeter, and the bolus material was

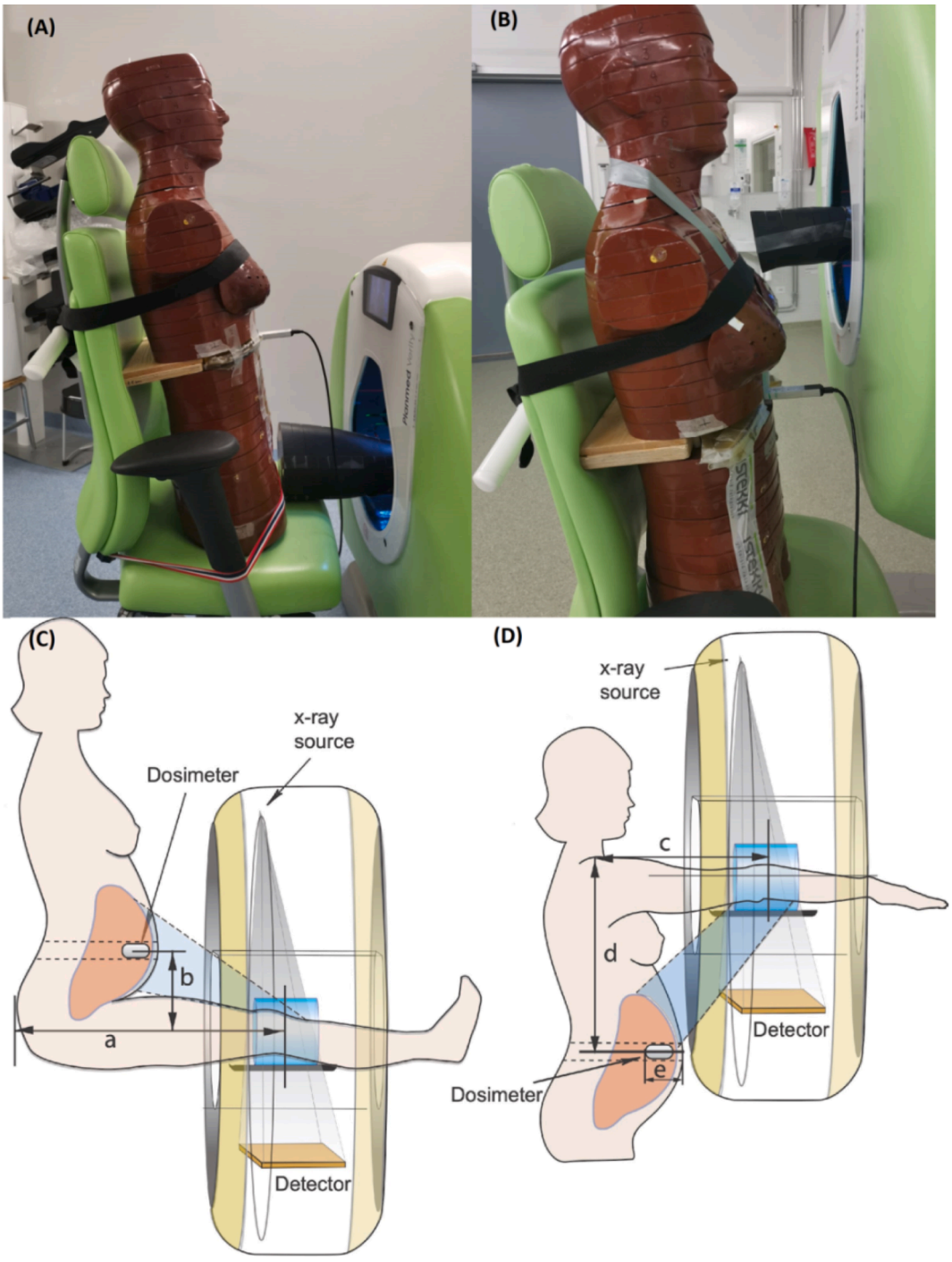

Fig. 2. Measurement setup and geometry. (A) Knee examination setup. (B) Elbow examination setup. (C) Knee examination geometry. a = 60 cm; for the dose measurements of the first trimester b = 15 cm, the second trimester b = 22.5 cm, the third trimester b = 35 cm; the depth of measurements from skin level e = 5,6,7 cm (D) Elbow examination geometry. c = 38 cm; for the dose measurements of the first trimester d = 50 cm, the second trimester d = 42.5 cm, the third trimester d = 30 cm; the depth of measurements from skin level e = 5,6,7 cm.

used to fill in the free space to mimic tissue attenuation and scatter properties inside the phantom. The detector was also covered with bolus material from both sides. The detector was inserted in the middle of each measurement slice in the mid-sagittal plane and the dose was measured at three different depths (the distance from the centre of the detector to the skin entrance) 5, 6 and 7 cm, therefore, investigating the effect of fetal depth. It has been shown previously that fetal depth can vary depending on the individual, the status of the bladder, the maternal body-mass index, placenta location, and other factors [23,24].

The Alderson phantom was positioned on the same chair where patients are examined in daily practice. CBCT scanner's height from the ground was 62.1 cm (knee measurements) and 107.5 cm (elbow measurements), body part support's height within the scanner bore was 49 mm (knee) and 66 mm (elbow). Gantry angle was 90 degrees for both setups (upright position). The phantom was forward-facing the CBCT scanner (here and further considered as 0-degree angulation). The knee and elbow phantoms were positioned to achieve as authentic examination geometry as possible. The measurement setups and geometries are shown in Fig. 2.

To investigate the effect of the thickness of the soft tissue layer (i.e. fat) on the abdomen region, fetal doses were also measured with extra bolus material placed upon the abdomen of the Alderson phantom (Fig. 3) (without an add-on device shield). Measurements with added one and two bolus material (30x30x1 cm) layers were made representing the 1 and 2 cm soft tissue layers. An incision in bolus material was made to allow dosimeter placement in the middle. For knee examinations the effect of extra tissue layer was investigated for the first trimester (slice 30), and for elbow examinations for the second trimester (slice 27).

In addition to measuring fetal doses, also entrance surface dose (ESD) was measured for the elbow examinations in the position with the highest fetal dose (without the add-on device shield). Elbow examinations were chosen as the measured fetal doses were higher than that observed in the knee examinations. In order to provide a simple and practical mean for fetal dose estimation based on measured ESD value, dose conversion factors were calculated to convert ESD to fetal dose when using clinical examination protocol with 92 kV - the measured fetal dose was divided by the corresponding ESD.

Furthermore, the effect of body angulation on the fetal doses was investigated for elbow examinations without an add-on device shield using phantom geometry that was as close as clinically possible to the real situation ensuring the possibility to turn the phantom. Similarly to the ESD assessments, the elbow examinations were chosen because the maximum fetal dose was higher than that attained in the knee examinations. Fetal doses were measured for three body angles – 0 degrees (anterior body facing the gantry), 45 degrees turn to the right side and 90 degrees turn to the right side (left side of the body facing the gantry). Phantom geometry in this case was as follows: c = 45.5 cm d = 30 cm etc., Fig. 2(D).

To evaluate the uncertainties that are related to the placement of the detector in the phantom, the series of measurements were also made with slightly changing detector placement in the phantom. Combined type B uncertainty was used to characterize the total uncertainty.

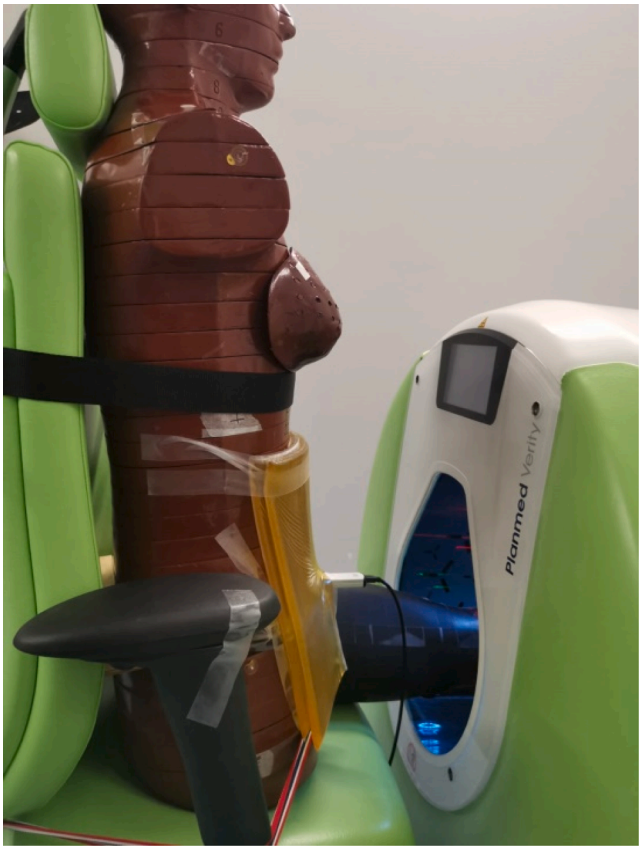

Fig. 3. Measurement setup with added bolus material for knee examination. For elbow examination bolus positioning was similar.

3. Results

3.1. Fetal doses at different stages of pregnancy

Table 2 shows the fetal doses from knee and elbow examinations using clinical protocols. Without any additional shielding the fetal doses were in the range of 3.4 to 6.0 μGy in knee examinations and in the range of 2.9 to 7.7 μGy in elbow examinations depending on the fetus position (depth and trimester). Table 2 also shows conversion factors for elbow examinations for calculating the fetal dose from the known the ESD.

3.2. Dose optimization methods

Shielding. The fetal doses with and without the add-on device shield are shown in Table 2. Percentage reduction in fetal dose was calculated in comparison to non-shielded case for the same setup and exposure parameters. The dose reduction with shielding was 80 % to 91 % for knee examinations and 59 % to 75 % for elbow examinations depending on the fetus position and the stage of the pregnancy.

Body angulation. The effect of body angulation on the fetal doses for elbow examinations is shown in Fig. 4. The doses were normalized against the maximum dose for each examination protocol. A gradual decrease in dose was seen when increasing body angulation from 0 (situation when the patient is facing the device directly) to 90 degrees. Decrease in dose was up to 22 % for 45 degree angle and 62 % for 90 degree angle (low kV protocol for both cases). Measurements showed similar relative decrease in dose for all three examination protocols studied.

Tube voltage. Fig. 5 to Fig. 8 present the effect of tube voltage on the fetal dose. Fig. 5 and Fig. 6 show the change in fetal dose when using examination protocols of three different tube voltages (Clinical protocol, Low kV protocol, High kV protocol, see Table 1). Results showed lower fetal doses for lower tube voltages for both, knee and elbow examinations. The decrease in fetal dose by lowering tube voltage is also seen when fetal dose is normalized with the dose level of the scan protocol ($CTDI_{vol}$) using the same tube current values (Fig. 7 and Fig. 8).

Tissue layer. An additional 2 cm soft tissue layer above abdomen region decreased fetal dose up to 19 % for knee and up to 21 % for elbow examinations (Fig. 9).

The uncertainty due to the placement of the detector in the phantom was found to be 5 %. The combined type B uncertainty of the fetal dose was evaluated as the weighted sum of variances and included the uncertainties from the detector positioning (5 %), repeatability (1 %), X-

Table 2
Fetal doses and error limits from knee and elbow examinations using clinical protocols with and without the add-on device shield and the percentage reduction in dose achieved by the use of the shield. Dose conversion factors are calculated as the corresponding fetal dose divided by the ESD.

Without shielding									
	1st trimester			2nd trimester			3rd trimester		
	Measurement depth								
	5 cm	6 cm	7 cm	5 cm	6 cm	7 cm	5 cm	6 cm	7 cm
Knee (μGy)	5.3 ± 0.6	4.5 ± 0.5	3.6 ± 0.4	6.0 ± 0.7	4.8 ± 0.6	3.9 ± 0.5	5.0 ± 0.6	4.2 ± 0.5	3.4 ± 0.4
Elbow (μGy)	3.3 ± 0.4	2.9 ± 0.4	2.5 ± 0.3	4.2 ± 0.5	3.7 ± 0.4	3.2 ± 0.4	7.7 ± 0.9	6.1 ± 0.7	5.0 ± 0.6
With shielding									
	1st trimester			2nd trimester			3rd trimester		
	Measurement depth								
	5 cm	6 cm	7 cm	5 cm	6 cm	7 cm	5 cm	6 cm	7 cm
Knee (μGy)	1.0 ± 0.1	0.9 ± 0.1	0.7 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.41 ± 0.05	0.36 ± 0.04
Reduction in dose (%)	81	80	80	85	84	85	91	90	89
Elbow (μGy)	1.4 ± 0.2	1.2 ± 0.1	0.9 ± 0.1	1.3 ± 0.2	1.1 ± 0.1	0.9 ± 0.1	1.9 ± 0.2	1.6 ± 0.2	1.4 ± 0.2
Reduction in dose (%)	59	60	64	70	71	72	75	74	73
Conversion factor							0.6	0.5	0.4

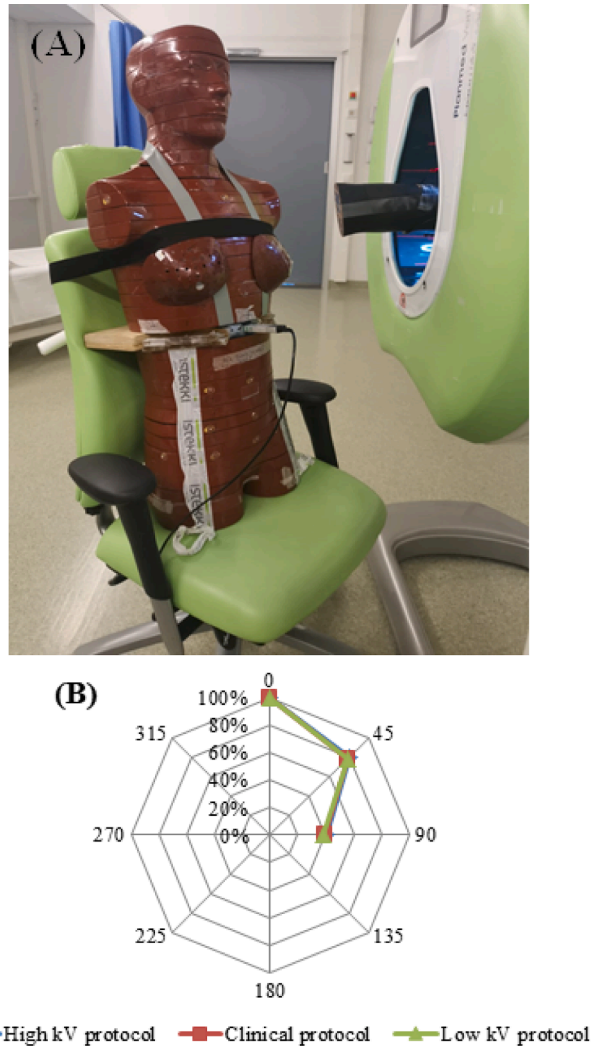

Fig. 4. (A) Phantom setup for the measurements with different body angulations (B) Changes in fetal dose for body angulation from 0 to 90 degrees during examination of elbow. Fetal doses are normalized against maximum dose for each examination protocol.

ray source variation (5 %) [25], and the detector uncertainty (10 %). Total uncertainty was evaluated as 12 %.

4. Discussion

This study evaluated fetal doses resulting from knee and elbow CBCT examinations of the mother, and various methods to reduce fetal doses. The results showed that the fetal doses were in the range of 3.4 to 6.0 μGy during knee examinations and 2.9 to 7.7 μGy during elbow examinations for clinical examination protocols. The doses varied depending on the depth of the fetus and the stage of pregnancy. In all cases the fetal doses were much lower than doses associated with any particular damage to the fetus (100 mGy) [26,27] and corresponded to for example less than three days of natural background radiation in Finland (2.88 μGy /d) [28]. Furthermore, the increase in the risk of childhood cancer would be produced by the doses of order of 10 mGy and in these circumstances the additional risk is approximately 6 % per Gy [29]. The fetal doses measured in this study were more than 1000 times lower than the dose of 10 mGy associated with the increased risk of childhood cancer. Thus, pregnancy should not be a reason to avoid or postpone clinically-justified CBCT examinations of musculoskeletal system and in any case the performed CBCT examination is not a justifying ground to terminate the pregnancy. The fetal doses caused by other CBCT examinations of musculoskeletal system (wrist, ankle, foot) are very likely even lower as the abdominal area of the mother is further away from the scan area, and the amount of radiation needed for the scan is also lower for smaller objects.

The fetal dose was lower when measured deeper in the body - the abdominal tissues of the mother absorb the scattered radiation and protect the fetus. The added bolus material layers above the abdomen region also decreased fetal doses. This indicates that fetus of a true pregnant women would very likely be more protected from scattered radiation than the measurements in the very thin phantom indicate and thus the fetal doses are likely even lower than measured. The possible adipose tissue as well the amniotic fluid would efficiently absorb parts of the scattered radiation before it reaches the fetus.

Although results showed that fetal doses are very low, the global ALARA principle (as low as reasonable achievable) calls for optimisation also on low dose levels. Thus different factors for the reduction of fetal doses were also investigated. The results showed the reduction of fetal doses up to 91 % for knee examinations and up to 75 % for elbow examinations by solely using the add-on device shield of the CBCT scanner. Similar results on organ dose reductions have also been reported previously [15,16]. The effect of the add-on device shield was greater for knee examinations. That could be explained by the design of the shielding which has an opening at the lower part and therefore creates less protection from the scattered radiation to parts that are below the examined body part (fetus in case of an elbow scan). According to the

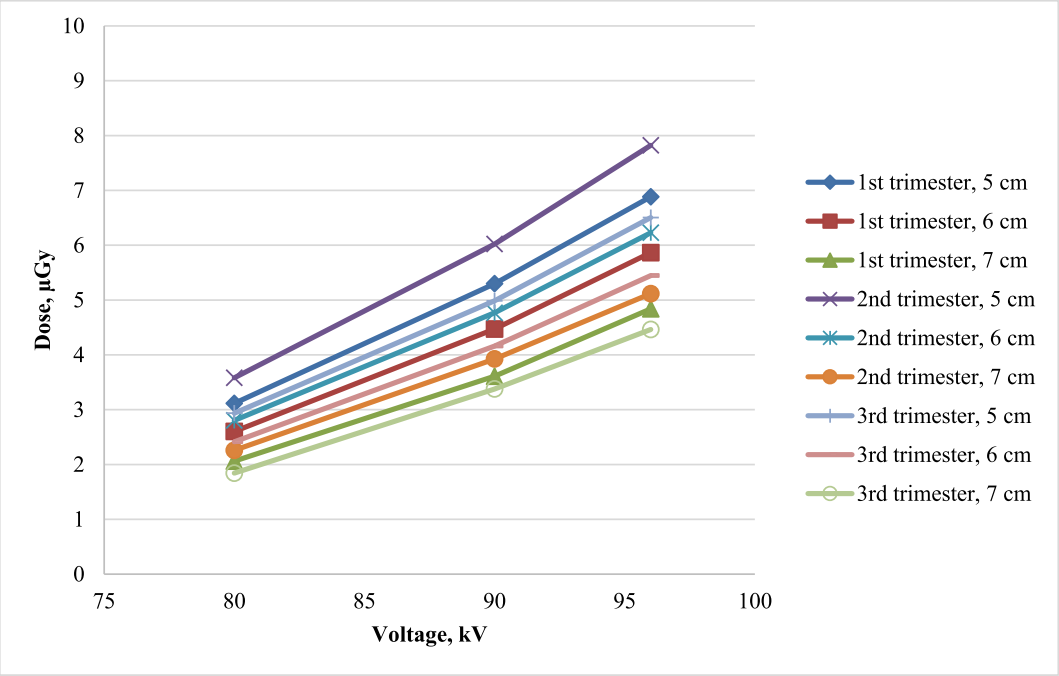

Fig. 5. The effect of the tube voltage to the fetal doses in knee examinations for different stages of pregnancy at different fetal depths (5, 6 and 7 cm).

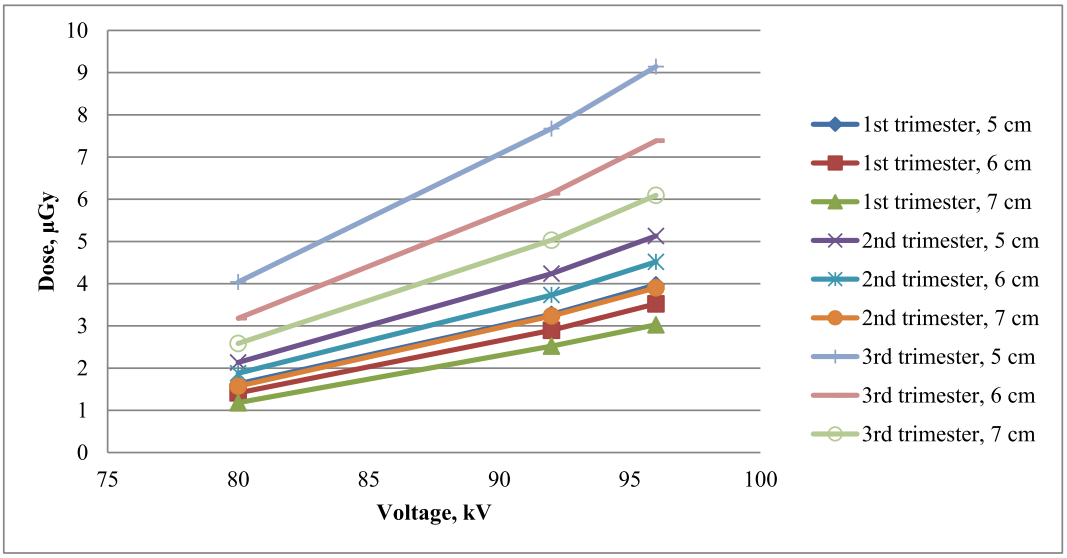

Fig. 6. The effect of the tube voltage to the fetal doses in elbow examinations for different stages of pregnancy at different fetal depths (5, 6 and 7 cm).

latest European recommendations [30], patient contact shielding outside the imaging field-of-view is not recommended anymore for many radiological examinations, including contact shielding to protect fetus. Thus, the add-on shield could be systematically used on the device to provide notable benefits but hardly any drawbacks. The add-on device shield is superior to contact shielding as it can be attached to the device easily (in less than 10 s) in a constant manner and does not carry the risks of creating additional artefacts or being uncomfortable to the patient.

Study showed that patient body position during examination has a notable effect on the fetal doses. Turning the body away from the device bore reduced the measured fetal dose for up to 62 %. True reduction of fetal dose may however be smaller as the geometrical efficiency of the detector creates more uncertainties in the dose measurements when increasing the body (and the detector) angulation. The detector is presenting a constant (±10 %) response over front axial range of 150 degrees. However, the detector is unable to detect photons coming from the back of the detector. When the body angle is increased more × rays are arriving from directions that are beyond the angular range of the detector. However, the body angulation, when practically feasible, could be considered as an easy method for fetal dose reduction as it increases the distance and amount of attenuating tissues between the fetus and the X-rays.

As expected, lower tube voltage also decreased the fetal doses. The fetal doses that were normalized by dose level ($CTDI_{vol}$) also decreased by lowering the tube voltage. As expected, the relative amount of scattering and penetration depth of the primary radiation decreased with decreasing tube voltage. This indicates that it could be possible to further reduce fetal doses by optimizing examination protocols towards lower tube voltages. However this must be done with caution in order to

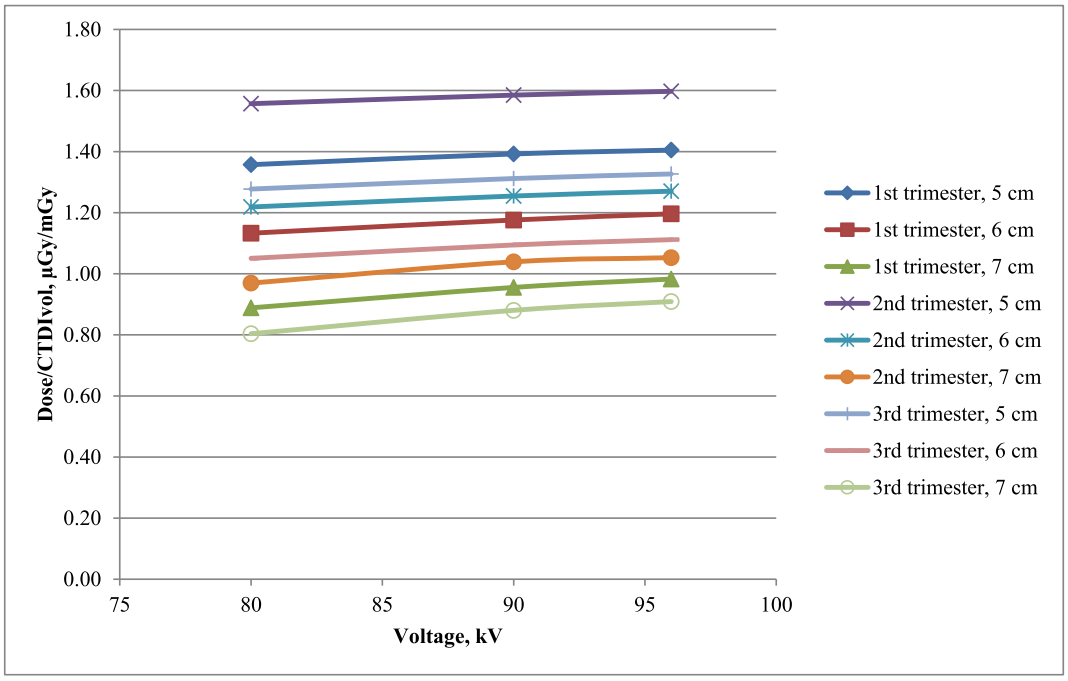

Fig. 7. Fetal dose normalized to CTDIvol in knee examinations depending on the tube voltage for different stages of pregnancy at different fetal depths (5, 6 and 7 cm).

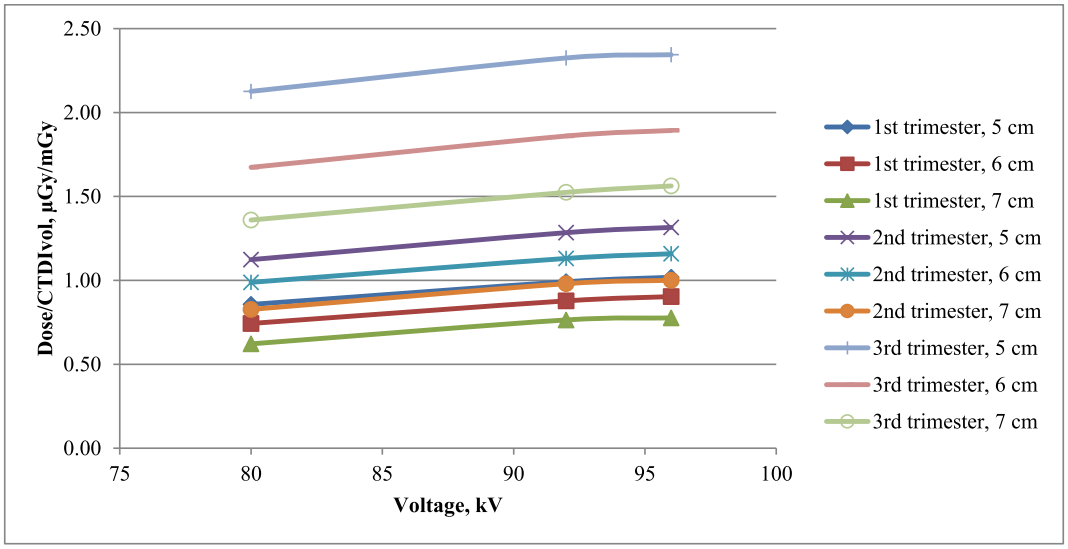

Fig. 8. Fetal dose normalized to CTDIvol in elbow examinations depending on the tube voltage for different stages of pregnancy at different fetal depths (5, 6 and 7 cm).

assure sufficient image quality that meets also the diagnostic needs. The measurements showed that the possible reduction in fetal dose could be up to 45 % in knee examinations and up to 51 % in elbow examinations if the voltage in current clinical examination protocols (92 kV knee, 90 kV elbow) is lowered to 80 kV and other parameters are left the same. The possible effect of tube voltage to fetal doses can be considered as minor; for example, the use of the add-on device shield is more efficient and secure way to protect the fetus in clinical practise.

The scan parameters in other studies [9,31] using CBCT for extremity examinations are in similar levels as in this study indicating that the results from this study should be applicable to other devices. The main differences on other devices would be connected to the positioning of the patient, availability of the shield and design of the bore or gantry.

Limitations of this study were related to the detector properties and phantom and measurement geometry. The main limitation of the detector is that the scattered photons coming from the back of the Xi Survey detector could not be detected. The interpretation of the results should be carried out with care since the backscattering radiation could not be taken into account. However, measured doses provide representative estimates of the fetal doses. Regardless of the measurement uncertainties the results were repeatable and constant. In the future, measurements could be done with phantoms representing different patient sizes with more added material in the abdominal region for later stages of pregnancy. The dose conversion factors give an estimate of fetal doses of elbow examinations using 92 kV if ESD is known, however further research could be done for different protocols, cone-beam geometries and collimation.

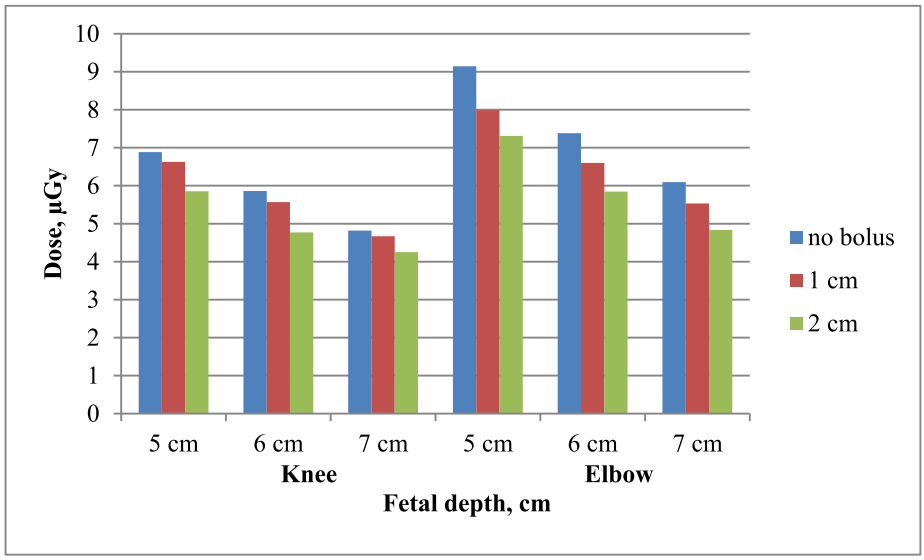

Fig. 9. The effect of tissue layer on abdomen for knee and elbow examinations for different fetal depth.

5. Conclusions

This study indicates that fetal doses from CBCT examinations of musculoskeletal system are low (3.4 to 6.0 µGy during knee examinations and 2.9 to 7.7 µGy during elbow examinations). It is safe to say that they do not produce a concern about radiation detriment to the fetus as they correspond to less than three days of natural radiation background. Different methods of fetal dose optimization (tube voltage, body angulation, add-on device shielding) were investigated to discover how much the fetal dose can be reduced using clinically available simple means. A variation in fetal doses between 0.5 and 7.7 µGy was found. In reality the fetus is shielded by the adipose tissue and amniotic fluid, and thus the dose levels are likely even lower.

It was found that the most efficient way to reduce fetal doses is to use the add-on device shielding. Also, fetal doses can be reduced notably by turning the body angulation away from the device bore. The use of these methods could be considered in daily practice if they are available and not uncomfortable for the patient.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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