UNIVERSITY OF GOTHENBURG

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FETAL DOSE ESTIMATION IN ABDOMINAL AND PELVIC CT EXAMINATIONS

M.Sc. Thesis

Olivia Carlstein

Essay/Thesis:	30 hp
Program and/or course:	Medical Physics
Level:	Second Cycle
Semester/year:	Spring/2020
Supervisor:	Maria Larsson & Maria Hultenmo
Examiner:	Magnus Båth

Abstract

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Keyword:	Fetal dose, abdominal CT examination, pelvic CT examination, phantom measurement

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Purpose: The purpose of this is study was to compare different methods for estimating the fetal dose, how much the different methods differ from each other and on which dose levels the fetal doses are estimated to.

Theory: A radiological procedure should always be justified and in the case of a pregnant patient the justification should include both the mother and the fetus. The absorbed dose to the fetus should be considered in the planning procedure, which means that you need to be aware of the potential fetal dose in advance. There are some risks associated with ionizing radiation for the fetus during pregnancy. These risks can be related to which stage of the pregnancy the woman is in and to the absorbed dose of the fetus. The associated risks are the deterministic effects which have a 100-200 mGy threshold and increase with the dose, these effects include abnormalities and mental impairments, and the stochastic effects which is the increased risk of inducing cancer. The doses in radiology are under normal circumstances low, but during CT examinations there is a risk that the fetal dose increases either in a single examination or repeated examinations, and for those cases a more accurate fetal dose estimation is necessary. If the dose is high and there is a high uncertainty in the dose calculations, there is a risk that the dose might come near or exceed the threshold value. In those cases, it is important to know which dose estimation method to use.

Method: To estimate the fetal dose, data from female pregnant patients CT examinations and phantom measurements were retrospectively used to estimate the fetal dose using different methods and programs. The patients were categorized into groups depending on the scan protocol and trimester, because the scan range and parameters are similar for each protocol. The different estimation methods and quantities that were used was $CTDI_{vol}$, SSDE, CT-Expo, CODE and VirtualDoseCT. The methods differ in their calculations, some of them take consideration to the patient's size and some of them the trimester or pregnancy week. The results from these methods and quantities were approximated to the fetal absorbed dose for comparison. The phantom measurement was made to compare the different dose estimation methods on the same "patient" during the same circumstances and to compare the results of fetal dose estimations from the patient measurements with a reference.

Results: The results showed that the patients in this study were larger in the second trimester than the third and that the best approximation for a patient circumference is an ellipse. Overall there was no large difference in the fetal dose estimations between the different methods and quantities. For the patients in their second trimester that underwent an abdominal CT examination, CT-Expo estimated the highest fetal dose, 17.3 mGy and SSDE estimated the lowest dose, 14.5 mGy. For the third trimester the lowest fetal dose was estimated to 11.6 mGy by VirtualDoseCT and the highest dose was estimated to 14.6 mGy by CT-Expo. The pelvic protocols are a low dose examination and the lowest estimated fetal dose was 0.7 mGy by VirtualDoseCT and the highest estimated dose was 0.9 mGy by SSDE. For the phantom measurement, CT-Expo consistently estimated the highest doses for all three trimesters, VirtualDoseCT estimated the lowest dose for the second and third trimester and $CTDI_{vol}$ showed the lowest dose for the first trimester.

Populärvetenskaplig sammanfattning

En datortomografi (DT)-undersökning är en vanlig diagnostisk undersökningsmetod. En DT använder sig av joniserande röntgenstrålning för att kunna avbilda kroppen i 3 dimensioner. Gravida patienter kan av flera olika anledningar behöva genomgå en DT-undersökning under sin graviditet och ligger då fostret nära eller inom undersökningsområdet så kommer det att få en stråldos. Medicinska undersökningar som innefattar joniserande strålning skall alltid vara berättigade, i fall med gravida patienter skall det här berättigande gälla för både mamman och fostret. Den absorberade dosen till fostret skall tas hänsyn till redan vid planeringen av undersökningen, detta innebär då att en uppfattning av den potentiella fosterdosen skall finnas redan innan undersökningen. Denna studie fokuserar på DT-undersökningar där fostret antingen helt eller delvis befinner sig inom undersökningsområdet. Risker för fostret beror på hur stor absorberad dos fostret får och vilken trimester kvinnan befinner sig i när hon undersöks. Gränsvärdet for deterministiska skador på ett foster är 100 - 200 mGy och ökar sedan med dosen, de deterministiska effekterna innefattar missbildningar eller mentala nedsättningar. Generellt håller sig DT-undersökningar långt under gränsvärdet. De stokastiska effekterna innefattar den ökade risken att fostret drabbas av cancer. Risken för cancer ökar linjärt med dosen men är oberoende av vilken trimester kvinnan befinner sig i vid undersökningstillfället. I denna studie har olika metoder för att uppskatta fosterdos undersökts, både retrospektivt på gravida kvinnors DT-undersökningar men också med hjälp av fantommätningar. I denna studien har olika metoder för att uppskatta fosterdos undersökts, de metoder som undersökts är $CTDI_{vol,}$ SSDE, CT-Expo, CODE och VirtualDoseCT. $CTDI_{vol}$ är ett mått på den medelabsorberade dosen inom en viss standarvolym, SSDE är en metod för att korrigera $CTDI_{vol}$ med hänsyn till patientens storlek. CT-Expo är ett beräkningsprogram skrivet i Excel där ekvivalenta doser till olika organ i patienten beräknas med hjälp av enkla fantom. CODE är ett program som är anpassat för att ta fram embryodoser med hänsyn till både vilken graviditetsvecka patienten befinner sig i och patientens omkrets och VirtualDoseCT är också ett program som är anpassat för att ta fram bland annat absorberade doser till foster. VirtualDoseCT kan för gravida patienter ta hänsyn till vilken trimester kvinnan befinner sig i. För denna studien har också ett fantom konstruerats med hjälp av ett bäckenfantom och magar gjorda av gelatin för att simulera de olika trimestrarna för en gravid kvinna. Fantomet är tänkt att kunna användas dels som referens till patientmätningarna dels för att kunna utvärdera dessa dosuppskattningsmetoder på en och samma ”patient” under samma förutsättningar. Syftet med den här studien är att jämföra olika metoder för fosterdosuppskattning, hur mycket dessa metoder skiljer sig från varandra samt vilka dosnivåer som foster kan erhålla vid DT-undersökningar.

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1 Abbreviations

AP	Anterior-Posterior
CODE	Conceptus Dose Estimation
CT	Computed Tomography
$CTDI_{vol}$	Computed Tomography Dose Index volume
$CTDI_{w}$	Computed Tomography Dose Index weighted
dFOV	displayed Field Of View
DICOM	Digital Imaging and Communications in Medicine
DLP	Dose Length Product
HU	Hounsfield Unit
LAT	Lateral
SF	Symphysis-Fundus
SSDE	Size Specific Dose Estimate

2 Introduction

Pregnant patients are exposed to ionizing radiation due to x-ray examinations every year which can create concerns for the future parents. A radiological procedure should always be justified and in the case of a pregnant patient the justification should include both the mother and the fetus. The absorbed dose to the fetus should be considered in the planning procedure, which means that you need to be aware of the potential fetal dose in advance (SSMFS, 2018:5).

Prenatal doses from justified and optimized radiological procedures do not give a noticeable increased risk for the fetus. But there are some risks associated with ionizing radiation for the fetus during pregnancy (ICRP84, 2000). These risks can be related to which stage of the pregnancy the woman is in and to the absorbed dose of the fetus. The associated risks that are often mentioned are the deterministic effects which include abnormalities and mental impairments. The threshold value for these effects are 100-200 mGy and the risk then increases with the dose. The stochastic effect is the increased risk of inducing cancer. There is no threshold for this effect, but the risk of developing cancer increases linearly with the absorbed dose and it is not correlated with the trimester (ICRP103, 2007). The risks of deterministic effects are highest during the first trimester during the organogenesis (Hall, DPhil, & Giaccia, 2012). Organogenesis is the stage during pregnancy where all the organs in the fetus are formed, and which organs that are affected by the radiation depends on which organs that are under development during the exposure. During the second trimester the risk of deterministic effects decreases and during the third trimester the risk is at its lowest. However, the deterministic effects can only occur if the threshold dose value is exceeded. According to ICRP 84 the woman has a right to know the potential associated risks the fetus may be exposed to before a radiological procedure (ICRP84, 2000). Therefore, a woman should always be asked if she is pregnant before the radiological procedure. If she is pregnant, she should be informed about the potential radiation associated risks for the fetus before the procedure. If diagnostic examinations that involves ionizing radiation are justified and optimized the risk for the mother if she does not undergo the procedure is generally larger than the potential radiation associated risk for the fetus. If the fetal dose does not exceed 100 mGy it should not be considered a reason for terminating a pregnancy, if the fetal dose is above this threshold value the woman should be appropriately informed of the potential risks for the fetus in order to take an informed decision, and the decision should also be based on the individual circumstances. In these cases, it is important to have an accurate fetal dose estimation and to be aware of the uncertainties in the estimation.

In conventional x-ray examinations during ordinary circumstances all examinations will result in fetal doses well below the threshold value, which also in general is true for computed tomography (CT) examinations. However, during CT and x-ray guided interventions there is a risk that the fetal dose increases, either in a single examination or repeated examinations, and for those cases a more accurate fetal dose estimation is necessary. If the dose is high and there is a high uncertainty in the dose calculations, there is a risk that the dose might come near or exceed the threshold value. There are different methods and programs for estimating the fetal dose, but as for most methods there may be some uncertainties using them and during examinations with risk of high doses the uncertainty and spread between the different calculation methods are especially important to take into consideration.

This study was focused on fetal doses in CT examinations with direct exposure to the abdomen/pelvis area. The overall aim of this study was to compare different methods for estimating the fetal dose, how much the different methods differ from each other and on which dose levels the fetal doses were estimated to. Of interest was also how user-friendly these methods are.

CT images and CT exposure parameters of pregnant women and an anthropomorphic phantom were used to study the level and accuracy of fetal doses estimated by different methods.

3 Materials and Methods

In order to estimate the fetal dose for CT examinations, different methods and computer software programs were applied and evaluated retrospectively on female pregnant patients and on phantom measurements. The patients and phantom data were divided into groups depending on the scan protocol used and trimester.

3.1 Study objects - Female pregnant patients and anthropomorphic phantom

3.1.1 Patients

3.1.1.1 Patient data

This study has been approved by the head of the radiological department, Sahlgrenska University Hospital as clinical development work. The results are only presented on group level.

There was a total of 26 patients in this study where the fetal dose was estimated retrospectively using the different dose estimation methods. One patient was scanned two times over the fetus and therefore two separate calculations were made and considered as two different examinations. The patients were divided into groups depending on the scan protocol, abdomen-other and pelvis, and according to trimester, see Table 1. The protocols named other consisted of aortic and kidney scans. The pelvis scan protocol is a low dose examination and the scan range does not cover the entire fetus, the results for this is shown by itself, but the abdomen and other scan protocols are shown together.

In the patient groups there was 5 women in their second trimester and 22 women in their third trimester that underwent CT examination, the distribution between the protocols can be seen in Table 1. There was no patient in in the first trimester. All the patients underwent their CT examinations at the department of radiology, Sahlgrenska University Hospital in Gothenburg during the years 2017-2019. In this study the patients circumferences, Anterior-Posterior (AP) and Lateral (LAT) dimensions were measured as exactly as possible in the CT images.

Table 1. Number of patients in this study for each protocol and trimester.

Scan protocol	Abdomen+Other*	Pelvis	Total
Trimester 2	5	0	5
Trimester 3	15	7	22

*Other protocols include aortic and kidney scans.

3.1.1.2 Patient CT examinations

The CT input parameters and the number of patients for the respective scan protocol and CT manufacturer can be found in Table 2. Most of the patients were scanned on a GE Optima CT 660 (GE Healthcare, Japan division) with 120 kV tube voltage, the rotation time for the abdomen protocols varied but it was mostly 0.8 s. Dose modulation was used for all the scans except for the pelvis protocols where a fixed tube current was used.

Table 2. CT protocol parameters for the examinations that the patients underwent. Values for $CTDI_{vol}$ (32cm), DLP mA and scan length are displayed as mean (min, max). For Siemens Somatom Force the tube current value for the examination was not retrieved.

	GE Optima CT660			Siemens Somatom Force		
Scan protocol	Abdomen	Pelvis	Other*	Abdomen	Pelvis	Other*
Number of patients	15	5	4	1	2	0
Tube voltage (kV)	100 or 120	120	120	90	150	-
Rotation time (s)	0.5, 0.6 or 0.8	0.5	0.5 or 0.6	0.5	0.25	-
Beam collimation (mm)	40	40	40	57.6	57.6	-
Pitch	0.984	1.375	0.984	0.6	1.5	-
Reconstructed slice thickness (mm)	5	5	5	5	3 or 5	-
Tin filter (Sn)	No**	No**	No**	No**	Yes	-
Dose modulation	yes	no	yes	yes	no	-
$CTDI_{vol}$ (mGy)	14(5,33)	1(0.9,1.2)	1(6,18)	5	0.36(0.35,0.37)	-
DLP (mGycm)	751(233,1583)	28(22,36)	524(276,779)	241	9(9,10)	-
Tube current (mA)	225(87,457)	30 or 40	212(119,341)	-	-	-
Scan length (cm)	47.4(43.8,52.7)	22.1(18.4,24.4)	44.8(35.4, 66.2)	47	20.2(20,20.4)	-

*Other protocols include aortic and kidney scans.
** Not selectable on an Optima.

3.1.2 Phantom

The phantom measurement was made to compare the different dose estimation methods on the same "patient" during the same conditions and to compare the results of fetal dose estimations from the patient measurements with a reference.

3.1.2.1 Phantom construction

The phantom was constructed using a pelvis phantom as a base representing the first trimester and phantom gel bellies representing the second and third trimester that was laid onto the pelvis phantom. The constructed belly was divided into three mold parts, the first two molds were constructed to represent the average growth of a belly at the end of the second trimester which is 8 cm. The third mold was then constructed to represent the average growth of a belly from the second trimester to the end of the third trimester which is 4 cm, the growth of the belly was then 12 cm in total. The size of the belly was decided using the symphysis-fundus (SF) measures from a study at Sahlgrenska University Hospital (Pay, Froen, Staff, Jacobsson, & Gjessing, 2013).

The molds for the bellies were constructed using thermoplastic nets that are usually used for patient fixation in radiation therapy for head and neck cancer. The thermoplastic net was heated, and a casting of the pelvis phantoms was formed to be used as a base mold, see Figure 1A. To build the second

trimester belly, a moldable cushion was formed into a belly, see Figure 1B and another net was laid onto the cushion to make the belly mold, see Figure 1C. The two molds were then melted together to form the second trimester mold. The same procedure was thereafter made to make the third trimester mold, but the base mold was instead formed over the surface of the second trimester. The two cavities were then filed with a gel with proportions 1:1.25, water respective gel powder (Dr Oetker, gelatin powder). The CT number in Hounsfield Unit (HU) value was checked for the gel by scanning in a CT to see how water equivalent the gel was.

The gel was then taken out of the mold and placed on the pelvis phantom when performing CT scans. The gel was taken out of the mold to minimize the air between the phantom and the gels. The first trimester was represented using only the pelvis phantom, the second trimester was represented using 8 cm high gels placed on the pelvis phantom and the third trimester was represented using the 8 cm plus 4 cm high gels on the pelvis phantom.

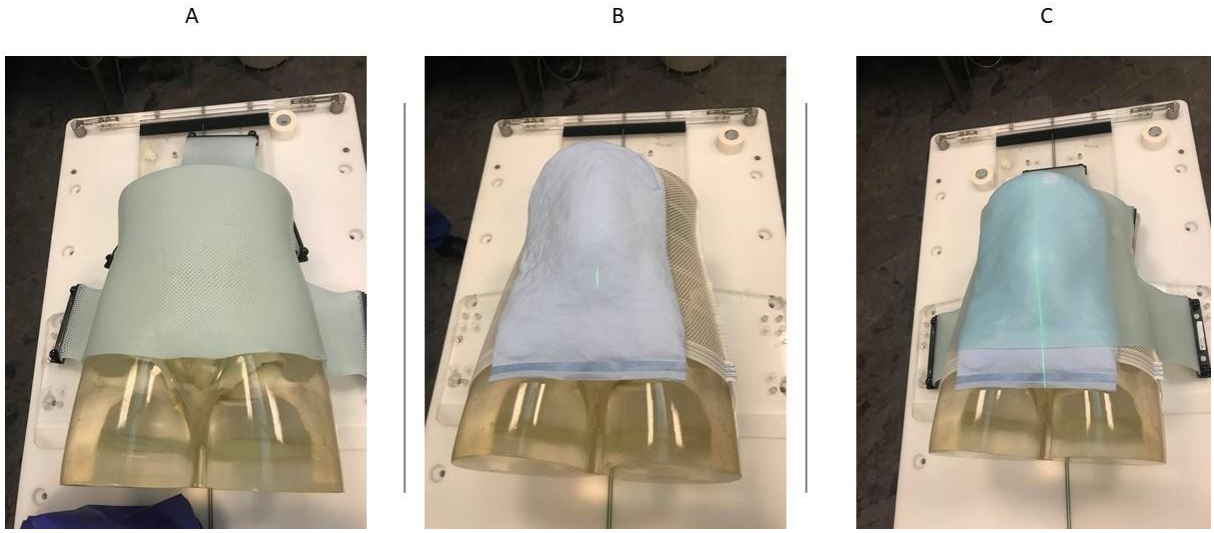

Figure 1.The thermoplastic form for the second trimester under construction. A) show the base mould, B) shows the mouldable cushion formed into a belly on the pelvis phantom and C shows the top net laid on top of the cushion.

3.1.2.2 Phantom scanning with clinical protocol

The phantom scanning was done on a GE Revolution CT (GE Healthcare, USA), see Table 3. The phantom was centered at the gantry isocenter, see Figure 2. For all the phantom measurements, an abdomen protocol without contrast, see Table 3, was used and for each trimester the table height was adjusted. The table height is set from the isocenter and to maintain the center the table height was lowered as the gel bellies were placed on top of the pelvis phantom, and a new scout was taken to consider the new size of the patient in order for the CT to perform a correct dose modulation. First a frontal scout was taken thereafter a lateral scout. The table was set to 113.5 mm, 153.5 mm and 173.5 mm from the isocenter for the first, second and third trimester respectively.

Table 3. CT protocol parameters for the phantom measurement. Values for $CTDI_{vol}$ (32cm), DLP and mA are displayed as 1st trimester, 2nd trimester, 3rd trimester.

	GE Revolution CT
Scan protocol	Abdomen
Tube voltage (kV)	120
Rotation time (s)	0.5
Beam collimation (mm)	40
Pitch	0.984
Reconstructed slice thickness (mm)	5
Tin filter (Sn)	-
Dose modulation	yes
$CTDI_{vol}$ (mGy)	6, 11, 15
DLP (mGycm)	219, 403, 520
Tube current (mA)	186, 427, 529

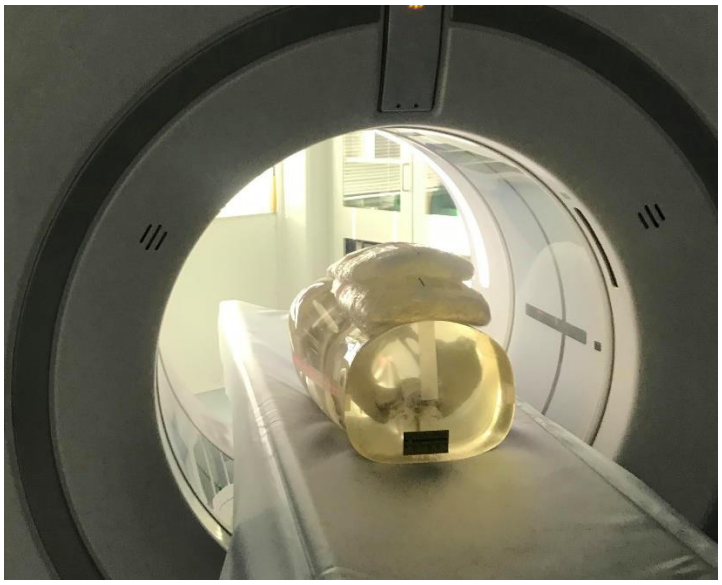

Figure 2. The pelvis phantom in the isocentre with the gels representing the second trimester.

3.2 Fetal dose estimations for patients and phantom

3.2.1 Dose estimation methods and quantities

Five different dose estimations methods and quantities was used in this study: The quantities Computed Tomography Dose Index volume ($CTDI_{vol}$) for a PMMA phantom, here diameter of 32 cm and Size Specific Dose Estimate (SSDE), as well as the dose estimation methods CT-Expo (Stamm & Nagel, CT-Expo version 2.5, 2017), Conceptus Dose Estimate (CODE) (Damilakis, Conceptus Dose Estimation, 2020) and VirtualDoseCT (Xu, Caracappa, & Crossin, 2020). These methods and quantities were used to estimate the fetal dose for different CT examinations for the patients and phantom described in Chapter 3.1. The different methods and quantities will present the absorbed dose to organs/tissues in different ways, $CTDI_{vol}$ will give the average absorbed dose within the whole scanned volume for a standardized CTDI phantom (16 or 32 cm in diameter) (mGy), in this study 32 cm PMMA phantom is used. SSDE will estimate the average absorbed dose to the abdomen/pelvis area, using the $CTDI_{vol}$ and a conversion factor depending on the patient's attenuation and cross

section compared to the 32 cm PMMA phantom (mGy), CT-Expo will give the equivalent dose to the uterus (mSv), CODE will give the absorbed dose to an embryo (mGy) and VirtualDoseCT will give the absorbed dose to the fetus (mGy). In this study the dose estimate by CTDIvol, SSDE, CT-Expo uterus dose, CODE embryo dose and VirtualDoseCT fetus dose is approximated to an absorbed dose to the fetus. CT-Expo and VirtualDoseCT also calculate other organ doses to the patient, and for comparison the dose to the patient bladder was noted. The dose to the bladder is given in equivalent dose from CT-Expo and absorbed dose from VirtualDoseCT. The equivalent dose is approximated to absorbed dose for comparison as the low Linear Energy Transfer (LET) radiation conversion factor to go from equivalent dose to absorbed dose is 1. The different methods require different inputs for calculation which can be seen in Table 4 such as tube voltage, tube current, rotation time, beam collimation and pitch.

Table 4. The required inputs for the different methods and quantities in order to be able to estimate a fetal dose. In common for all the software programmes was the tube voltage (kV), tube current (mA), rotation time (s), beam collimation (mm) and scan length (cm).

	CTDIvol	SSDE	CT-Expo	CODE	VirtualDoseCT
Pregnancy week				X	
Trimester					X
$CTDI_{vol}$ (mGy)	X	X	(X)		
Scan lenght (cm)			X	X	X
AP+LAT (cm)		X			
Fetus depth (cm)				X	
Circumference (cm)				X	
CT scanner			X		X
Filter (Sn)			X		
Tube voltage (kV)			X	X	X
Tube current (mA)			X	X	X
Rotation time (s)			X	X	X
Total beam collimation (mm)			X	X	X
Table feed per rotation (mm)			X		
Reconstructed slice thickness (mm)			X		
Number of scaned series			X		
Pitch				X	X
$CTDI_W$ (mGy/ 100 mAs)				X	X
$CTDI_{100,\ free\text{-}in\text{-}air}$ (mGy/ 100 mAs)				X	

3.2.1.1 Computed Tomography Dose Index volume ($CTDI_{vol}$)

$CTDI_{vol}$ represents the average absorbed dose within the scan volume for a standardized CTDI phantom (AAPM96, 2008). Standardized CTDI phantoms is a Polymethyl Methacrylate (PMMA) phantom with either 16 cm in diameter to represent the head or 32 cm in diameter to represent the body. The SI unit is mGy.

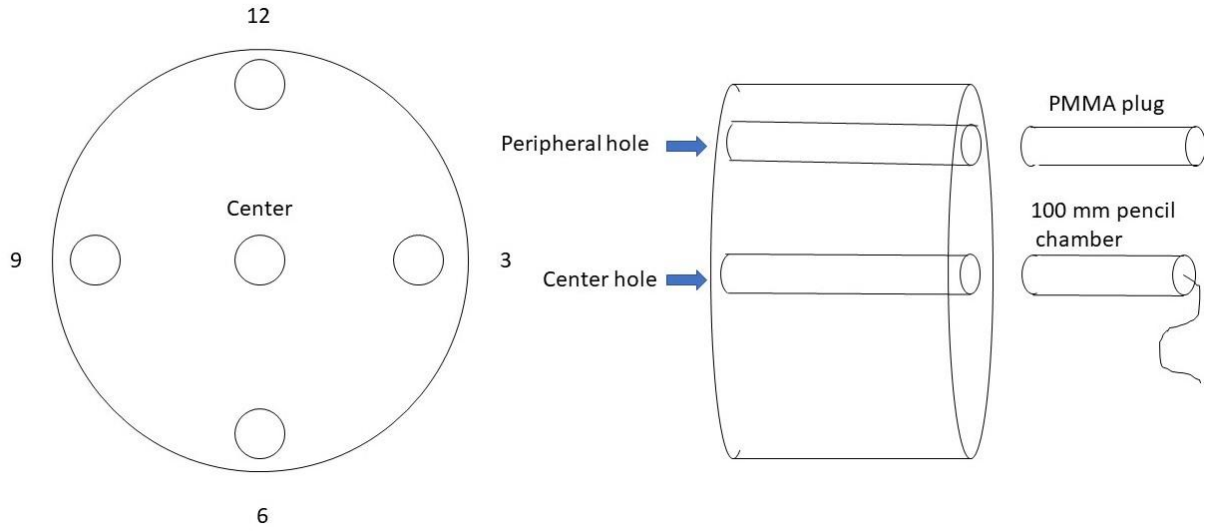

Figure 3. The general set up for the $CTDI_{100}$ measurement in a standard CTDI PMMA phantom. There are two standard CTDI phantoms, 16 cm or 32 cm in diameter representing head or body respectively, both are 15 cm in length. The pencil chamber is 100 mm long and is placed either at the centre or at the periphery holes of the phantom. Unused holes may be plugged with PMMA rods. This picture is modified from an illustration in AAPM 204 (AAPM204, 2011).

$CTDI_{100}$ is defined as:

Equation 1

$$CTDI_{100} = \frac{1}{nT}\int D(Z)dz$$

Where n is number of detector rows used during the scan and T (mm) is the nomial thickness of each row (Hsieh, 2009). Together they represent the nominal collimated beam width (mm). D(z) (Gy) is the dose absorption distribution in z for a single axial scan. $CTDI_{100}$ is measured using a standard CTDI phantom (AAPM96, 2008), see Figure 3. $CTDI_{100}$ is measured at the center and at the periphery of the phantom, resulting in $CTDI_{100}^{Center}$ or $CTDI_{100}^{Periphery}$ respectively. The quantity measured for the defined $CTDI_{100}$ is air kerma, represented in the units mGy.

The weighted CTDI (mGy) combines dose information at different locations, it represents a mean dose value for one rotation (Hsieh, 2009). It does not take into consideration the dose received when a helical scan is performed, $CTDI_W$ is calculated as:

Equation 2

$$CTDI_W = \frac{1}{3}CTDI_{100}^{Center} + \frac{2}{3}CTDI_{100}^{Periphery}$$

For helical examinations the dose in CT is related to spiral pitch, the $CTDI_{vol}\ is\ defined\ as$:

Equation 3

$$CTDI_{vol} = \frac{CTDI_W}{pitch}$$

Pitch is defined as the ratio of the table feed (mm) per 360° gantry rotation to the nominal collimated beam width.

$CTDI_{vol}$ is also used to estimate the Dose Length Product (DLP) (mGycm), DLP is computed as:

Equation 4

$$DLP = CTDI_{vol} * lenght\ of\ scan$$

In this study the $CTDI_{vol}$ and DLP from each CT examination was noted, the scout was not included. All values referred to the body CTDI phantom (32 cm). $CTDI_{vol}$ was in this study used to estimate the absorbed fetal dose.

3.2.1.2 Size Specific Dose Estimate (SSDE)

SSDE is a method for adjusting the $CTDI_{vol}$ (32cm) value from a CT examination to fit a specific patient geometry better and get a more reality-based dose value then if the dose refers to a standard phantom size and material. SSDE takes into consideration the size of the patient and adjust the $CTDI_{vol}$ value. The adjustments are based on the standardized PMMA phantoms, 32 cm or 16 cm (body and head respectively).

$CTDI_{vol}$ adjustments can be made by using conversion factors based on either the AP, LAT or AP+LAT dimensions of the patient or the effective AP, LAT or AP+LAT dimensions, measured in cm, see Figure 4A. The effective dimensions can directly be compared with the phantom diameter.

The $CTDI_{vol}$ is multiplied with the conversion factor, f_{size}^{32x}, based on the AP and/or LAT measures. Conversion factors for a wide range of patient sizes (AP, LAT, AP+LAT, effective diameter) can be found, for both a 32 cm PMMA phantom and a 16 cm PMMA phantom in the AAPM report 204 (AAPM204, 2011). The SSDE (mGy) is calculated according to:

Equation 5

$$SSDE = f_{size}^{32x} * CTDI_{vol}^{32}$$

for the 32 cm diameter PMMA phantom, (AAPM204, 2011). Recommended is to use the AP+LAT dimension since this measure takes into account two patient dimensions which results in a conversion factor that have better accordance to theoretic and measured values, than when just one patient dimension (AP or LAT) is used (Burton & Szczykutowicz, 2018). The conversion factor also converts PMMA to water equivalent material (AAPM220, 2014).

In some of the clinical images in this study the whole patient could be seen and the entire AP and LAT dimensions could be measured, see Figure 4A, but in the other cases the patient was larger than the displayed field of view (dFOV) and the patient was cut on either the AP, LAT dimensions or on both, see Figure 4B. For the women that did not fit entirely in the dFOV the AP and LAT were measured in two ways. The AP and LAT were first measured for the visible length and then measured when approximating the women's size outside the dFOV, see Figure 4B.

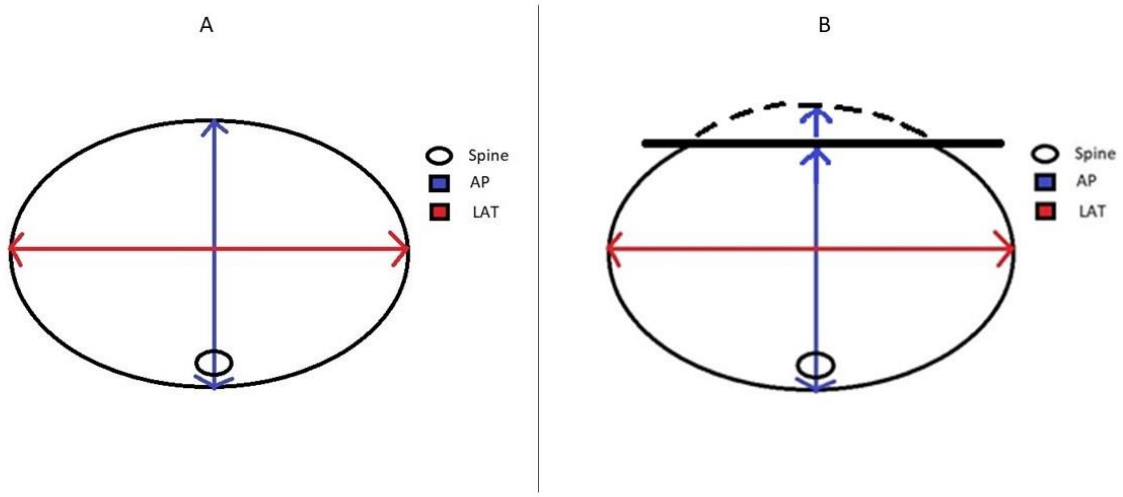

Figure 4. A) shows the AP and LAT dimensions in an axial CT slice with the spine as a reference. B) Shows an example if the AP dimension was cut off where the long blue arrow represents the visible part of the AP dimension. The dotted line represents the approximate size of the patient outside the dFOV and the long + short blue arrow represents the approximate AP dimension. If the LAT dimension was cut off the same method was applied there.

In this study the AP and LAT dimensions were measured separately using a digital ruler in the axial CT image at the widest part of the pregnant women's belly in the axial CT series, the fetal dose was estimated using both the visible and approximated AP+LAT dimensions. The conversion factor was based on the 32 cm PMMA phantom shown for patients AP+LAT in Figure 5. The estimated SSDE value representing the patient dose to the abdomen/pelvis area was used as an estimate of the fetal dose.

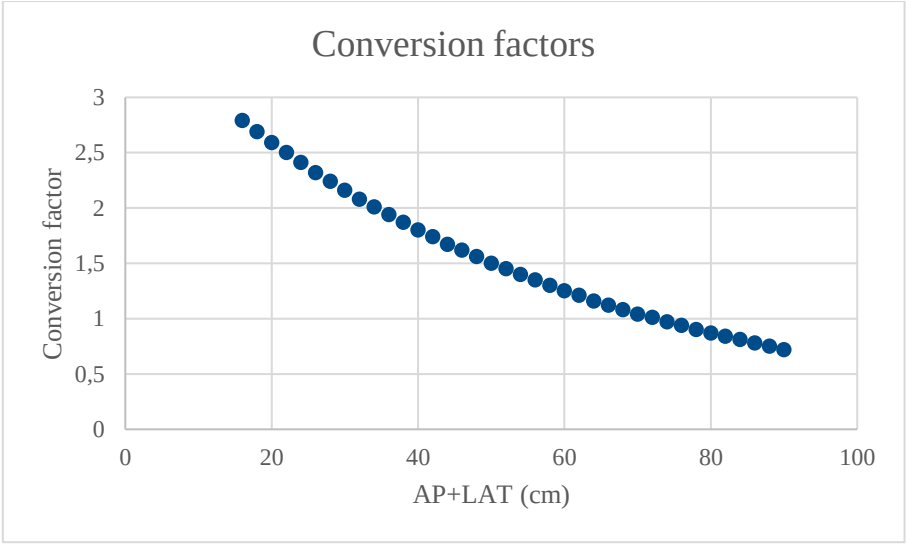

Figure 5. The conversion factor f_{size}^{32x} for the AP+LAT measures for the 32 cm PMMA phantom used for estimating SSDE (AAPM204, 2011).

3.2.1.3 CT-Expo

CT-Expo v 2.5 is a method that estimates the equivalent tissue organ doses, H_T (mSv) and the effective dose (mSv) for different organs in a standard patient phantom for different CT examinations

(Stamm & Nagel, 2017). CT-Expo is a MS excel application using Monte Carlo simulations that requires CT specific inputs to give organ specific dose estimates. It is written in Visual Basics and is based on computational methods. A description of these methods can be found in the book 'Radiation exposure in computed tomography by Hans Dieter Nagel, 2002'. All calculations are based on standard patients, represented by the well-defined mathematical phantoms "ADAM", "EVA", "CHILD" and "BABY". The female phantom Eva represents a normal sized woman with no possibility to change size or select a trimester. Her standard is >18 y, 160 cm and 60kg, see Figure 6. The phantom construction involves Monte Carlo simulations and is built up by different shapes and boxes.

When applied to the clinical patient first you need to choose age and gender, thereafter the scan range over the area of interest of the patient, see Figure 6.

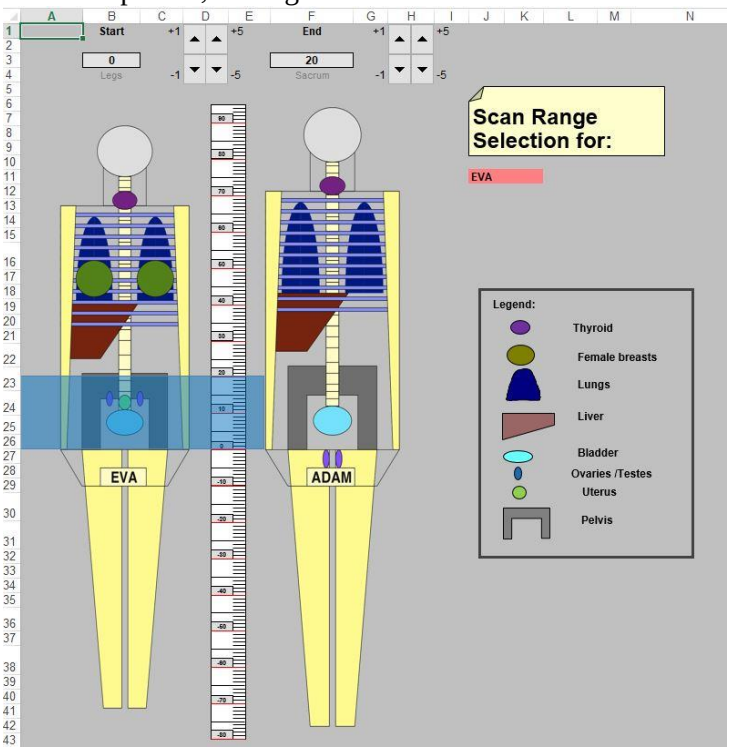

Figure 6. The female phantom to the left with a scan range over the pelvis area, the picture is a copy from the program (Stamm & Nagel, CT-Expo version 2.5, 2017)

Other parameters inputs that are required is CT scanner $CTDI_{vol}$, scan range, tube voltage, tube current, rotation time, tin filter, beam collimation, table feed per rotation, reconstructed slice thickness and number of scan series, see Table 4. The specific CT protocol inputs for the patients can be found in Table 2 and for the phantom in Table 3. CT manufacturers and scanners are chosen with the used bow tie filter size and eventual tin filter. The selection of spiral/axial mode and dose modulation are also needed as input for an accurate dose estimation.

In this study the CT scanner was chosen with a large bow-tie filter. Spiral mode and dose modulation were used in all the calculations. The scan range in the clinical CT images were matched to the scan range of the phantom in CT-Expo. The total scan length and the organs that were included within the clinical scan range were prioritized in the matching with CT-Expo.

An adjusted tube current ("adjusted mA") was used in CT-Expo, since the dose modulation in the CT examinations are not the same as the mathematical dose modulation applied in CT-Expo. The tube current input was varied systematically until the DLP and the $CTDI_{vol}$ from the CT examination and CT-Expo matched as closely as possible. This value was noted as "adjusted mA" for each

examination. Additionally, for the phantom scans the mean tube current for the rotation (same mean value for the whole beam collimation) used in the different parts of the phantom are found in the DICOM tags. For the phantom the tube current (mA) specified in the slice with the largest AP measure (named "mA in slice") was used in as an alternative tube current input apart from the adjusted tube current. The CTDIvol and DLP given by CT-Expo when using "mA in slice" were noted.

In this study the dose to the uterus was approximated to the absorbed fetus dose. The dose to the bladder of the patient was also noted.

3.2.1.4 Conceptus Dose Estimation (CODE)

CODE is an online program with different modules, the CT module in CODE estimate the absorbed dose (mGy) to an embryo in different gestational ages for different CT examinations (Damilakis, CODE user manual, 2020). The embryo dose coefficients are produced by Monte Carlo simulations and normalized to $CTDI_{free\ in\ air}$. The CT module in CODE consists of four different mathematical phantoms representing an individual during the post-conception period, 1st, 2nd and 3rd trimester. The phantoms are generated using a software and the abdominale circumference of these phantoms are 88.7 cm, 88.7 cm, 102.3 cm and 108.2 cm, respectively. And for the post-conception period and 1st trimester the embryo depth is defined as the distance from the embryo to the anterior abdominal wall and was set to 9 cm, this input was not required for the last two gestational ages (week 13-25 and 26-40). The four different gestational ages which are defined as 0-7 weeks, 8-12 weeks, 13-25 weeks and 26-40 weeks.

CODE uses a computer simulated image of a lateral CT scout and two bars that can be dragged across the image to set the scan range to match with the clinical CT examination, see Figure 7. The required inputs are tube voltage, tube current, rotation time, pregnancy week, scan range, fetus depth (only for the post-conception and 1st trimester), circumference (at the widest part of the belly), pitch, $CTDI_W$ $(mGy/100mAs)$ and $CTDI_{free\ in\ air}$ $(mGy/100\,mAs)$. These required input parameters can be found in Table 4. $CTDI_{free\ in\ air}$ $(mGy/100\,mAs)$ and $CTDI_W$ $(mGy/100\,mAs)$ for this study were found in the manual for the specific CT, but if necessary they can be measured respectively calculated using equations 1 and 2.

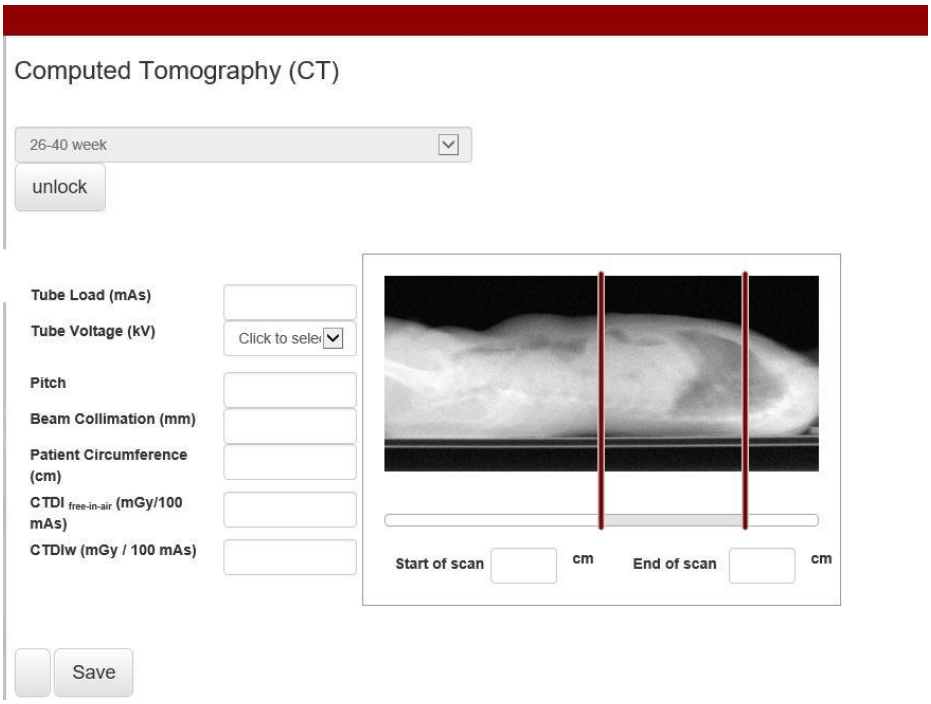

Figure 7. The view of CODE in the computed tomography examination section. Shows an example of the parameter inputs for the third trimester, the picture is a copy from the program (Damilakis, Conceptus Dose Estimation, 2020).

The specific CT protocol inputs used in this study can be found in Table 2. The patient circumference in this study was measured as exactly as possible by laying out small digital rulers around the visible parts in the axial CT slice in the clinical CT images where the patient or phantoms bellies were at its widest. A simplified method for estimating the circumference by approximating the patient to a circle or an ellipse was also performed. If the entire woman could be seen within the dFOV the visible circumference equals the exact size, but in the cases where the woman was cut off on either side only the visible circumference was measured, see Figure 4A.

For the circle approximation the following equation was used:

Equation 6

$$Circumference = \pi * Diameter$$

Where the diameter was either the AP or LAT dimension of the patients at the widest part of the patient.

For the ellipse approximation the following equation was used:

Equation 7

$$Circumference = \pi\left(\frac{a}{2}+\frac{b}{2}\right) - \sqrt{(3\frac{a}{2}+\frac{b}{2})(\frac{a}{2}+3\frac{b}{2})}$$

Where a and b are the AP and LAT dimension, respectively.

For the phantom measurement where a first trimester could be scanned, the fetus depth was set to 9 cm according to the program definition for the calculations on the first trimester. The fetus depth is very

individual, but the phantom used in this study is thin, so 9 cm was reasonable. The total length of the scan range and the included organs were then matched in the CODE phantom and calculations were made using either the mean tube current for the entire scan length given in DICOM tags in the abdominal/other examinations, or the fixed tube current value for the pelvic examinations which is also found in the DICOM tags. For the phantom scans which had specified tube current values for each slice, the fetal dose was also calculated with "mA in slice" as an input. The tube voltage choices in CODE was limited and, in the cases, where an exact tube voltage could not be found the nearest possible voltage was chosen, the difference between the tube voltages was maximum 10 kV and could be both higher or lower.

3.2.1.5 VirtualDoseCT

VirtualDoseCT is an online program that uses Monte Carlo simulation software to estimate the absorbed dose (mGy) for different organs and tissues for a wide range of phantoms (Xu, Caracappa, & Crossin, 2020). For a pregnant woman there are three phantoms available, that is either 3, 6 or 9 months pregnant. VirtualDoseCT uses the Monte Carlo based method for modeling various parameters such as photon energy spectrum, beam collimation, beam filtration, tube current and scan protocols. In addition to the total fetus dose, VirtualDoseCT can provide the absorbed dose to the fetal brain, fetal skeleton and fetal soft tissue. In this study all of fetus doses were of interest, but the total fetus dose was the result compared to the other methods. The absorbed dose to the bladder was also noted for comparison.

VirtualDoseCT has several different scan protocols (for example pelvis or abdomen/pelvis), here the scan range are predetermined over the pelvis or abdomen/pelvis part of the body, but there is an option to manually alter the scan range. VirtualDoseCT uses an anatomic image, in which it is possible to manually change the scan range, see Figure 8. There are two green boxes that can be dragged across the image to represent the beginning and end of the CT scan, next to the green boxes two axial CT images are shown (the beginning and end of the scan), see Figure 8. The beam collimation can be varied but appears automatically with a pre suggested size when the CT manufacturer and scanner is chosen. There is a choice for tube current modulation which is not available in the trial version, used in this study.

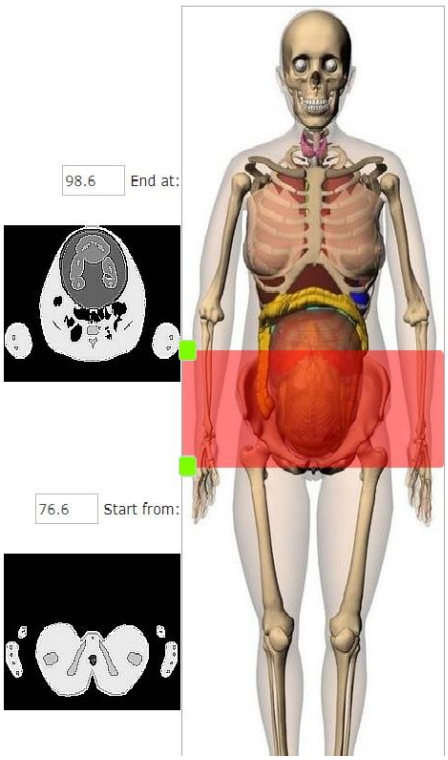

Figure 8. The computer simulated phantom of a pregnant woman in the third trimester with a scan range over the pelvis area. The green boxes represents the beginning and end of the scan range and next to the green boxes, two axial CT images are shown (the beginning and end of the scan range), the picture is a copy from the program (Xu, Caracappa, & Crossin, 2020).

Required inputs for VirtualDoseCT are tube voltage, tube current, rotation time, trimester, CT scanner, pitch, beam collimation, scan range and $CTDI_w$ $(mGy/100\,mAs)$. The required parameter inputs can be found in Table 4 .There is a possibility to choose either a body or head bow tie filter. The scan range in this study was manually specified. $CTDI_w$ $(mGy/100\,mAs)$ was taken from the manual for the specific CT.

Calculations were made using either the mean tube current for the entire scan length given in DICOM tags in the abdominal/other examinations, or the fixed tube current value for the pelvic examinations which is also found in the DICOM tags. For the phantom examination which had specified tube current values for each slice the fetal dose was also calculated with “mA in slice” as an input.

3.3 Error in calculations

Errors in the calculations are presented as the standard error of the mean.

The standard error of the mean depends on both the standard deviation and the sample size, by the relation:

Equation 8

$$Standard\ error\ of\ the\ mean = \frac{standard\ deviation}{\sqrt{number\ of\ samples}}$$

The standard error falls as the sample size increases, but the standard deviation will not tend to change as the size of the sample increases. Standard error of the mean indicates the uncertainty around the estimate of the mean measurement (Altman & Bland, 2005).

4 Results

4.1 Study objects- Female pregnant patients and antropomorphic phantom

The patient measurements that were used during this study for the different dose estimation methods can be seen in Table 5. The mean circumference was 107.5 cm for the patients in the second trimester and 103.9 cm for the patients in the third trimester. As can be seen in Table 5 the visible and approximative measures did not vary much from each other. But the LAT showed a higher value than AP in both the second and third trimester. The first row represents the patient circumference measured as exactly as possible, when comparing the circumferences estimated with an ellipse or circle the results show that the ellipse shows the most accurate circumference. The circle with AP as diameter underestimated the circumference and the circle with LAT as diameter overestimated the circumference. The patients' circumference was larger for the women in the second trimester compared to women in their third trimester.

Table 5. The measures (in cm) for the female pregnant patients.

	2nd trimester			3rd trimester		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Visible patient circumference	107.5	95.9	129.7	103.9	88.6	114.3
AP visible	28.9	25	36.2	29.2	24.5	35
AP approximative	28.9	25	36	29.6	24.5	37
LAT visible	38.3	33.7	44	35.3	30.5	40.9
LAT approximative	38.7	33.7	46	36.9	30.5	45
AP+LAT visible	67.2	60	80	64.5	56	71
AP+LAT approximative	67.6	60	82	66.5	56	82
Ellipse visible AP and LAT	106.1	94.6	125.9	101.5	88.1	111.5
Circle visible AP	90.9	78.5	113.7	91.5	76.9	109.9
Circle visible LAT	120.1	105.8	138.2	110.9	95.8	128.4

For the phantom scanning at 120 kV the results from the gel on the pelvis phantom gave a CT number of 9.4 HU with the deviation of 11.1 HU, which is near tissue equivalent (i.e 20-40 HU) (Lev & Gonzales, 2002). The dimensions for the phantom can be seen in Table 6, where the whole phantom could be seen within the dFOV, see Figure 11. Figure 11 shows the widest part of the phantom in the axial CT slices for the respective trimester. The difference between the mean value for the patient and phantom circumference in the second trimester was 8.1 cm and in the third trimester it was 1.8 cm.

Table 6. The measures (in cm) for the constructed pregnant phantom.

	Circumference	AP	LAT	AP+LAT
Trimester 1	86.2	22	29	51
Trimester 2	99.5	30	29	59
Trimester 3	105.7	33	29	62

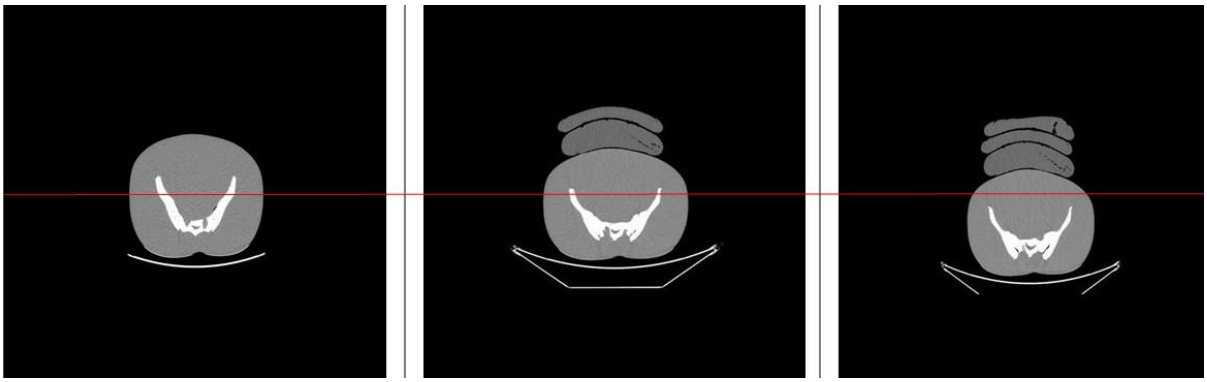

Figure 11. The axial CT slice of the widest part of the phantom for the respective trimester. It shows the first, second and third trimester from left to right, the red line represents the isocentre. The table height for the first trimester was 113.5 mm, for the second trimester it was lowered to 153.5 mm and for the third trimester it was lowered to 173.5 mm

4.2 Fetal dose estimations for patients and phantom

The estimated fetal absorbed doses for the abdomen and other protocols from different methods and quantities are shown in Figure 12. The SSDE results shown are the mean value between the results calculated using the visible AP and LAT measures for and using approximate AP and LAT measures. The CT-Expo results are shown as the mean value between the results calculated with the specific CT slice tube current and the mean tube current for patients and phantom respectively. The CODE results are shown as the mean value between the results from the specific CT slice tube current and the mean tube current with the visible patient/phantom circumference respectively. The results for VirtualDoseCT are shown as the mean value between the results from the specific CT slice tube current and the mean tube current for patients and phantom respectively.

Comparing the different estimation methods and quantities, CT-Expo consistently showed the highest estimated fetal absorbed doses independent of the scan protocol or trimester. For the second trimester, SSDE estimated the lowest fetal absorbed dose, 14.5 mGy, compared to 17.3 mGy using CT-Expo, and for the third trimester VirtualDoseCT estimated the lowest fetal absorbed dose, 11.6 mGy, compared to the highest fetal absorbed dose, 14.6 mGy, estimated with CT-Expo. The difference between the dose estimations was approximately 3.0 mGy in both trimesters and scan protocols.

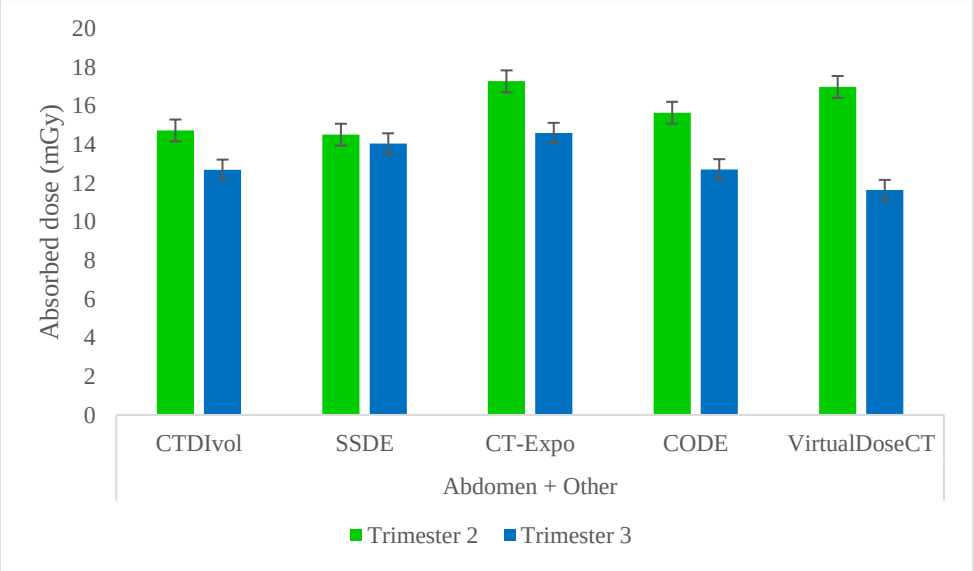

Figure 12. The fetal absorbed doses estimated by using the various methods and quantities for the abdomen and other scan protocols for the patients. The green bars represent the second trimester and the blue bars represent the third trimester. The error bar shows the standard error.

For the pelvis protocols with patients only in the third trimester, the lowest estimated fetal absorbed dose was 0.7 mGy by VirtualDoseCT and the highest estimated fetal absorbed dose was 0.9 mGy by the SSDE method, see Figure 13. The difference between the dose estimation methods was 0.2 mGy. The fetal absorbed doses for the pelvis protocols were much lower compared to the abdomen and other protocols due to fact that they are a low dose protocol.

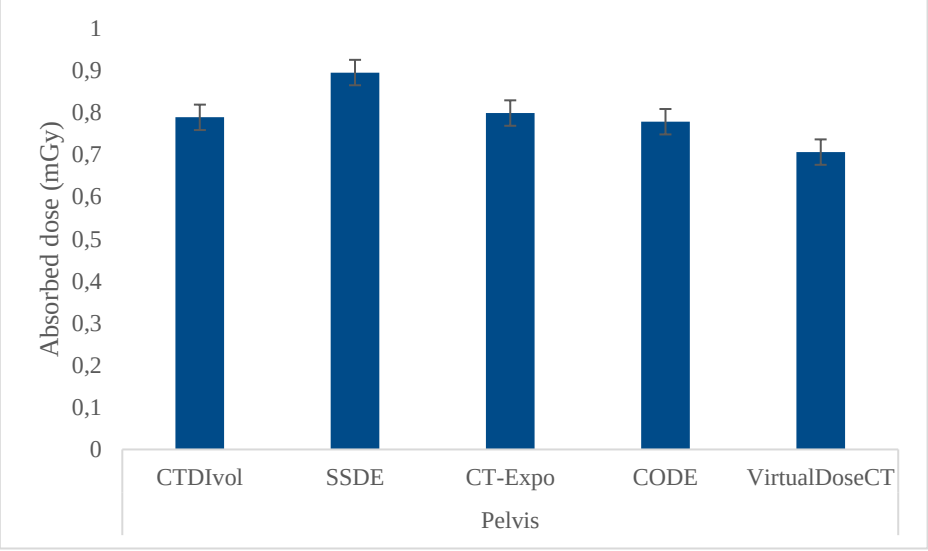

Figure 13. The fetal absorbed dose for patients in their third trimester examined with the pelvis protocols were estimated using the various methods. The error bar shows the standard error.

For the SSDE method a comparison between the estimated fetal absorbed dose using the AP and LAT measure of the visible anatomical contour of the patient and of the approximate anatomical contour was made (see Figure 4 A-B). The results for the abdomen and other protocols are shown in Figure 14. For the abdomen and other protocols for the second trimester, the fetal absorbed dose was estimated to 14.6 mGy by using the visible measures and for the approximate measures the fetal absorbed dose was estimated to 14.4 mGy, meanwhile for the third trimester, the fetal absorbed dose was estimated to

14.3 mGy and 13.8 mGy, respectively. The difference between the mean dose estimations for the abdomen and other protocols was 0.2 mGy in the second trimester and 0.5 mGy in the third trimester.

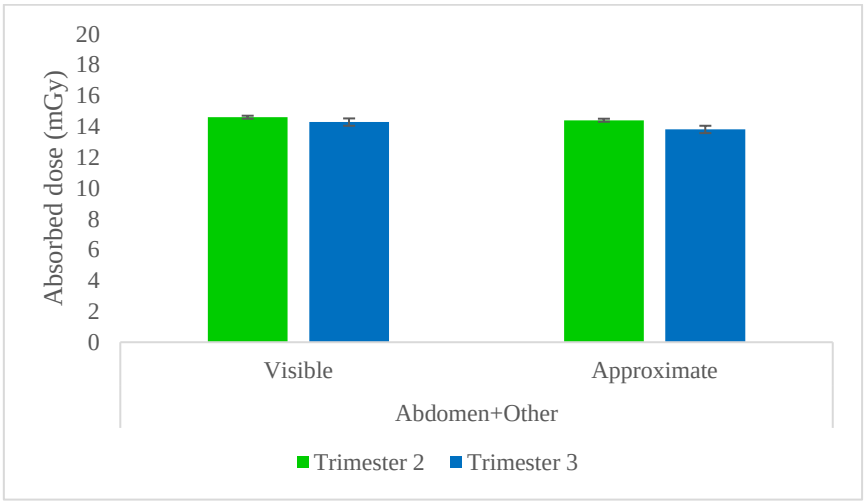

Figure 14. The estimated fetal absorbed doses for the patient using either the visible measures of the patient or the approximate measures of the patient in the SSDE method for the abdomen and other protocols. The error bar shows the standard error.

In Figure 15 the results of the comparison between using the visible or approximate measures in the SSDE method in the pelvis protocols with patients in the third trimester are shown. The estimated fetal absorbed dose using the visible measures was 0.92 mGy and using the approximate measures the estimated fetal absorbed dose was 0.87 mGy. The difference between the dose estimations was 0.05 mGy.

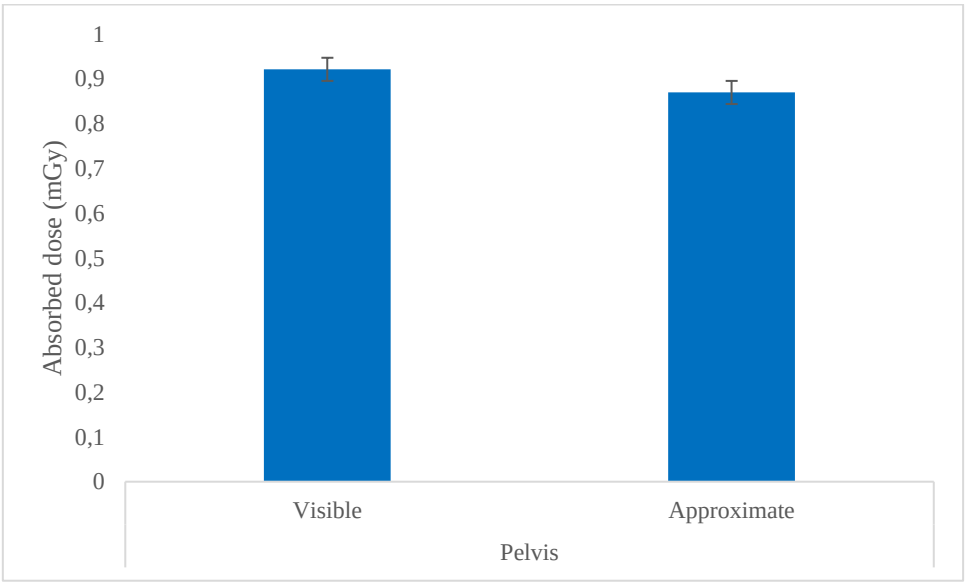

Figure 15: The estimated fetal absorbed doses for the patients using either the visible measures of the patient or the approximate measures of the patient in the SSDE method for the pelvis protocols. The error bar shows the standard error.

For the phantom measurement, when estimating the fetal absorbed dose with CT-Expo, using the tube current for the specific CT slice gave a DLP value for the examination that was higher in every trimester than the given DLP value for the examination, see Table 7. The estimated fetal absorbed

dose when using either the specific CT slice tube current or the mean tube current for the abdomen protocol is shown in Figure 16. The difference between them was 0.6 mGy for the first trimester, 5.6 mGy for the second trimester and 6.1 mGy for the third trimester.

Table 7. The different tube currents and their corresponding DLP for the different trimesters in the phantom measurement.

Trimester	Mean tube current	DLP for the examination	CT slice tube current	DLP in CT slice
1	175.7	219.3	186	234
2	324.4	402.8	427	537
3	418.7	519.9	529	665

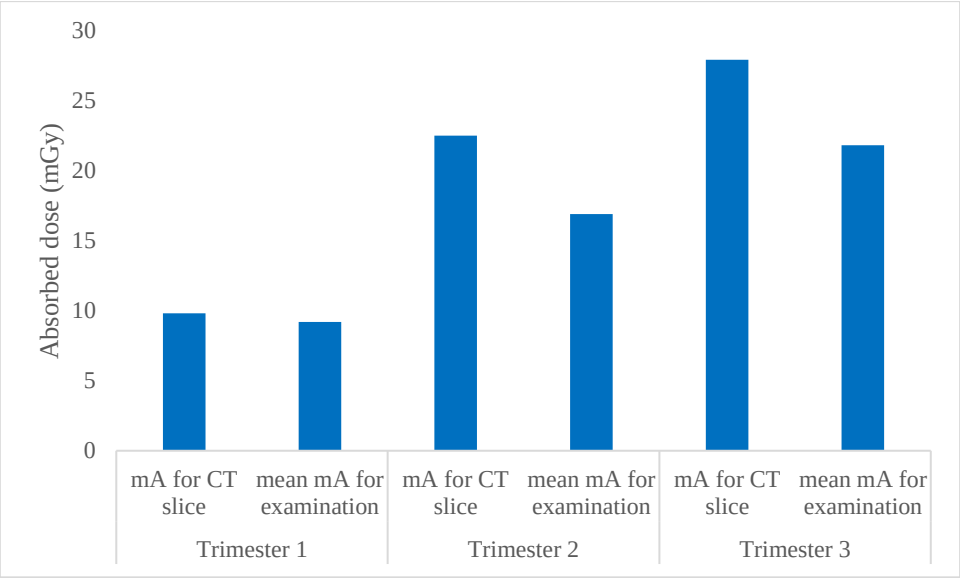

Figure 16. The fetal absorbed dose for the phantom for the different trimesters when using either the specific CT slice tube current or the mean tube current for the examination in CT-Expo. The error bar shows the standard error.

For the CODE method, dose estimations were made both using the visible patient circumference and using the approximate circumference in the form of an ellipse and a circle calculated from the AP or LAT measures. Figure 17 shows the results for the abdomen and other protocols. The estimated mean fetal absorbed dose using the visible patient circumference in the second trimester was 15.6 mGy. Approximating the circumference using an ellipse gave the estimated mean fetal absorbed dose of 15.9 mGy, resulting in a 0.3 mGy difference. Approximating the circumference to a circle using the AP measure as the diameter gave the estimated mean fetal absorbed dose 18.8 mGy, resulting in 3.2 mGy difference. Approximating the circumference to a circle using the LAT measure as the diameter instead gave the estimated fetal absorbed dose of 13.3 mGy, resulting in 2.3 mGy difference. For the patients in the second trimester scanned with the abdomen and other protocols the ellipse measure gave the lowest difference in mean fetal absorbed dose estimation compared to using the more exact patient circumference. For the patient in the third trimester scanned with the abdomen and other protocols the estimated mean fetal absorbed dose using the more exact patient circumference is 12.7 mGy. Using the ellipse approximation gave the mean fetal absorbed dose 12.9 mGy, the circle approximation with AP as diameter gave 14.3 mGy, and the circle approximation using the LAT as diameter gave 11.7 mGy, resulting in 0.2, 1.6 and 1 mGy difference, for respective approximation in the third trimester. For the third trimester the ellipse approximation also gave the lowest difference in dose estimation.

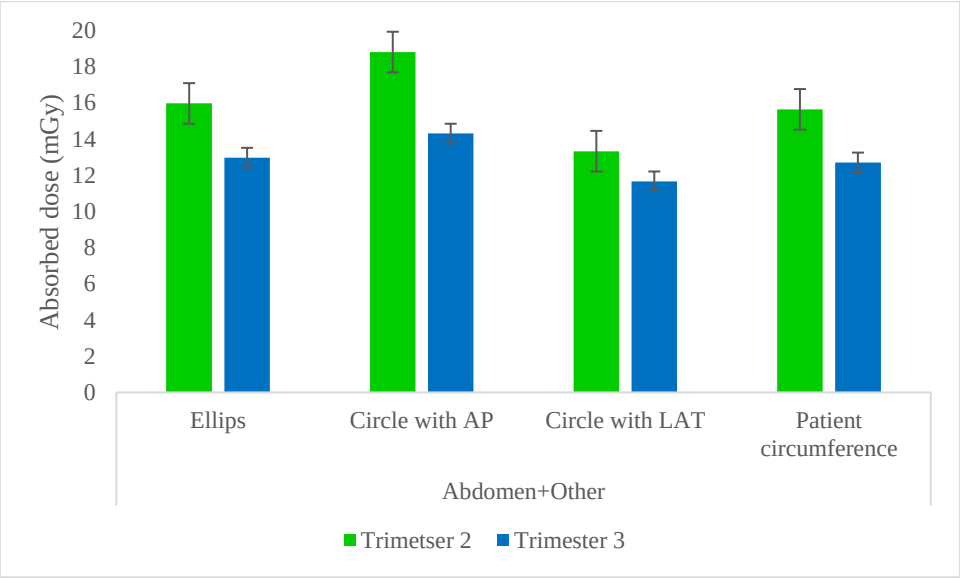

Figure 17. The estimated fetal absorbed doses for the patients using either the exact patient circumference or approximating the circumference to an ellipse or circle for the CODE method in the abdomen and other protocols. The error bar shows the standard error.

If instead looking at the pelvis protocols the results for the mean fetal absorbed dose estimation using CODE with either the more exact patient circumference, approximating it to an ellipse or a circle with patients in the third trimester are shown in Figure 18. The estimated fetal absorbed dose using the more exact patient circumference was 0.78 mGy. Using the ellipse approximation gave 0.80 mGy, the difference is 0.02 mGy. The circle approximation with AP as diameter gave 0.87 mGy, the difference is 0.09 mGy. The circle approximation using the LAT as diameter gave 0.73 mGy, the difference is then 0.05 mGy. For the third trimester in the pelvis protocols the ellipse approximation gave the lowest difference in dose estimation.

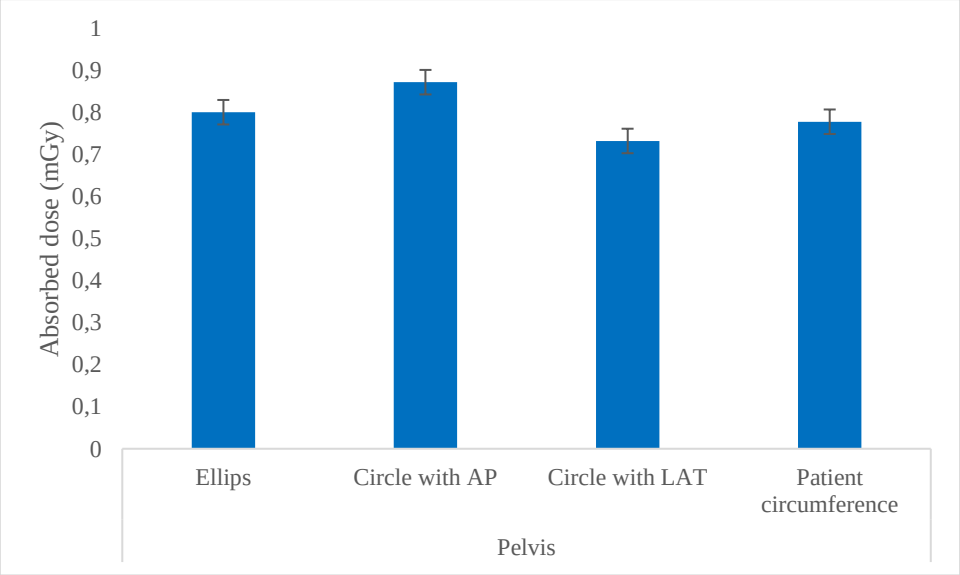

Figure 18. The estimated fetal absorbed doses for the patients using either the more exact patient circumference or approximating the circumference to an ellipse or circle for the CODE method in the pelvis protocols. The error bar shows the standard error.

For comparison of the dose estimation methods the patients absorbed dose to the bladder was evaluated using CT-Expo and VirtualDoseCT. The results for the abdomen and other protocols with

patients in the third trimester are shown in Figure 19. For the abdomen and other protocols, the absorbed dose to the bladder of the pregnant woman using CT-Expo was 22.6 mGy and using VirtualDoseCT the bladder dose was 9.6 mGy, the difference between them is 13 mGy.

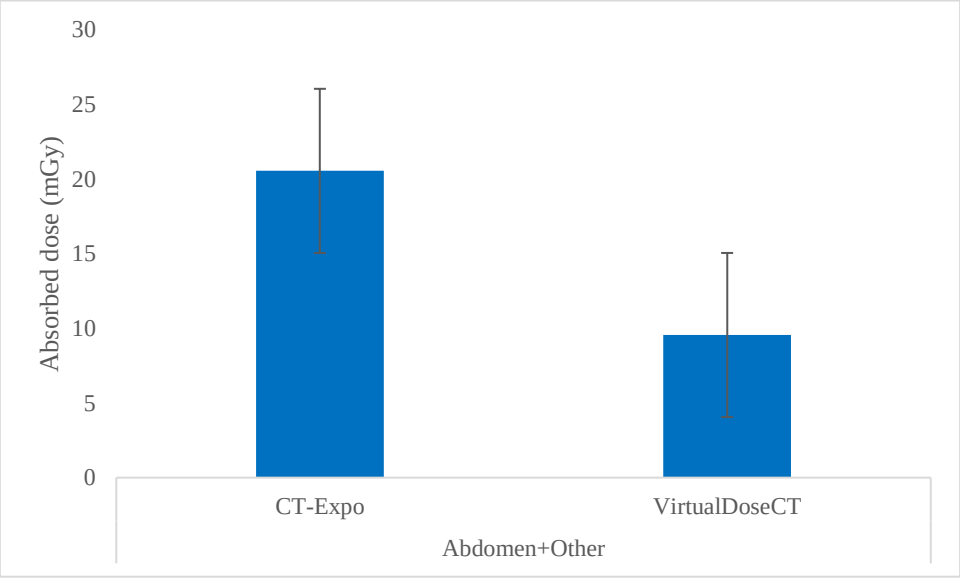

Figure 19. The absorbed dose to the bladder for a pregnant woman in the third trimester for an abdomen protocol and other protocol estimated using either CT-Expo or VirtualDoseCT. The error bar shows the standard error. For CT-Expo there was 10 patients and for VirtualDoseCT there was 15 patients.

Using VirtualDoseCT different organ doses of the fetus were also estimated. The organs that VirtualDoseCT estimate are the fetal brain, skeleton and soft tissue. Figure 20 shows the estimated absorbed doses for these organs and the total absorbed dose to the fetus. For the patients scanned with the abdomen and other protocol in second trimester the estimated doses were 13.2, 57.5 ,17.5 and 16.9 mGy respectively. For the third trimester the doses were 8.1, 36.3, 12.8 and 12.2 mGy respectively. The fetal skeleton receives the highest absorbed doses.

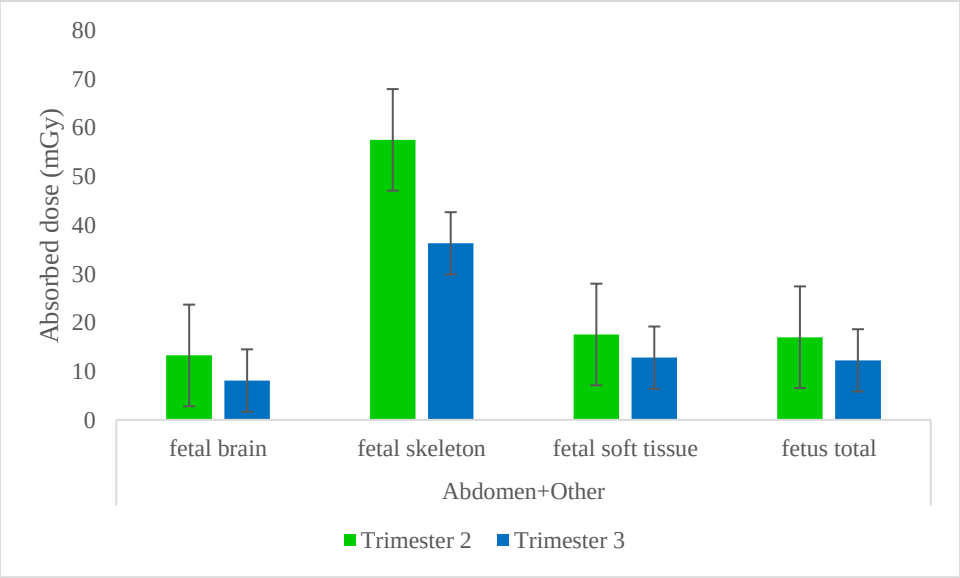

Figure 20. The absorbed doses to different organs of the fetus and the total dose to the fetus estimated by VirtualDoseCT for patients scanned with the abdomen and other protocols. The error bar shows the standard error.

For the pelvis protocol the results for the estimated doses to the different part of the fetus and the total dose to the fetus by VirtualDoseCT are shown in Figure 21. The estimated doses were 0.6 mGy to the fetal brain, 2.1 mGy to the fetal skeleton, 0.7 mGy to fetal soft tissue and 0.7 mGy in total absorbed dose to the fetus. The fetal skeleton receives the highest doses.

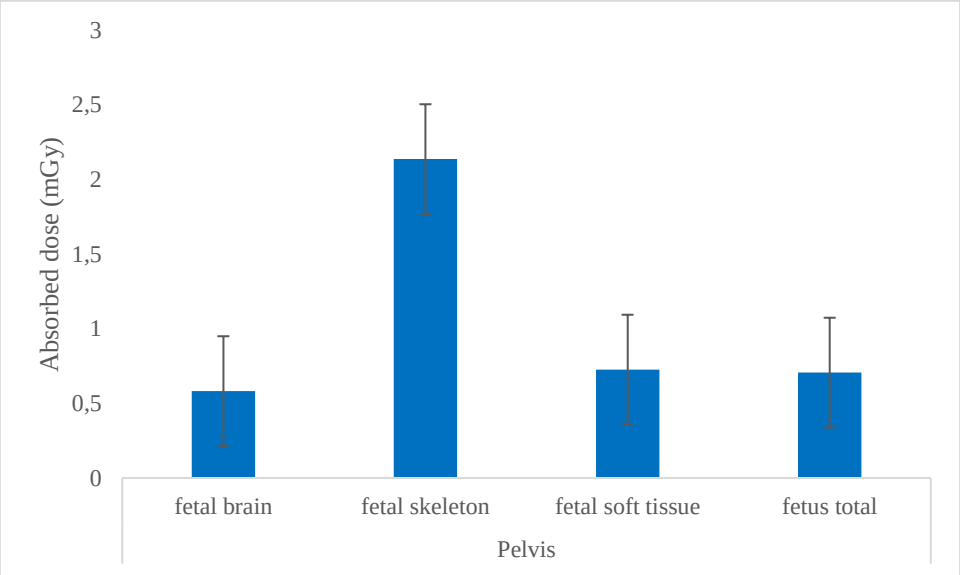

Figure 21. The absorbed doses to different organs of the fetus estimated by VirtualDoseCT for patients scanned with the pelvis protocols. The error bar shows the standard error.

The result of the fetal absorbed dose estimation for all three trimesters for the phantom measurement scanned with the abdomen protocol is shown in Table 8. Comparing the fetal absorbed dose estimate of each trimester for respective dose estimation method, CT-Expo consistently estimated the highest fetal absorbed doses independent of trimester and VirtualDoseCT estimated the lowest fetal absorbed doses for trimester 2 and 3 and $CTDI_{vol}$ showed the lowest dose for trimester 1, see Figure 22. The maximum difference in dose between the dose estimation methods was 3.4 mGy for the first trimester, 8.5 mGy for the second trimester and 10 mGy for the third trimester. The difference between the methods seemed to get higher with the trimesters, especially for CT-Expo.

Table 8. The different dose estimations for the phantoms different trimesters.

	CTDIvol	SSDE	CT-Expo	CODE	VirtualDoseCT
Trimester1	6.1	9.0	9.5	7.5	6.6
Trimester2	11.2	14.3	19.7	14.4	12.2
Trimester3	14.5	17.5	24.9	15.6	14.4

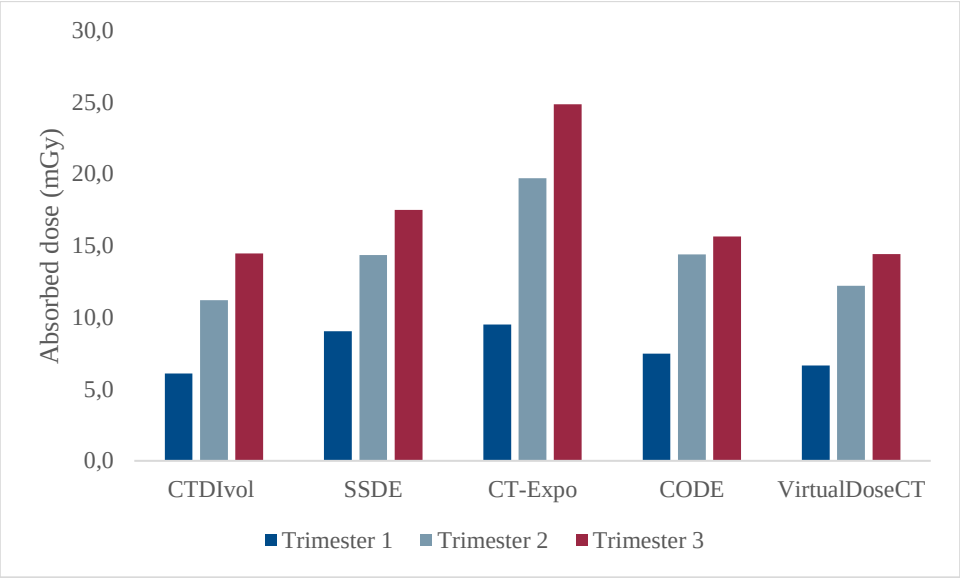

Figure 22. The different fetal absorbed dose estimations for each trimester for the phantom.

The doses to the fetal brain, skeleton, soft tissue and total fetal absorbed dose estimated with VirtualDoseCT were also noted for the phantom measurements. For the first trimester, VirtualDoseCT does not estimate an absorbed dose to the fetal skeleton, otherwise the doses to the fetal skeleton received the highest absorbed dose as can be seen in Figure 23. The absorbed doses for the first trimester were 6.2, 0, 6.5 and 6.5 mGy for the fetal brain, skeleton, soft tissue and total fetus respectively. For the second trimester the doses were 8.2, 35.5, 10.9 and 10.5 mGy, and for the third trimester the doses were 8.6, 37.8, 13.3 and 12.7 mGy, respectively. All the doses increased with the trimester.

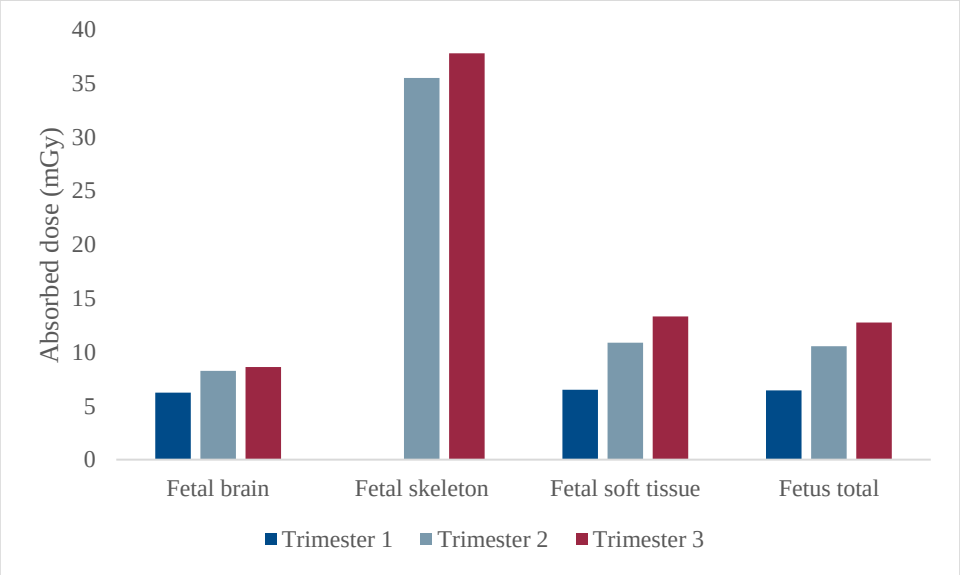

Figure 23. The absorbed doses to different organs of the fetus and the total dose to the fetus for the phantom estimated by VirtualDoseCT for the phantom measurements using an abdomen protocol.

5 Discussion

In this study, the range of mean fetal absorbed dose estimated by different methods for the pelvis protocols was 0.7-0.9 mGy, for the abdomen and other protocols it was 15-17 mGy for the second trimester and 12-15 mGy for the third trimester. When comparing the different methods, the abdomen/other protocols gave the highest dose which is reasonable since they primarily are standard dose CT examinations compared to the low-dose CT pelvis protocols. The abdomen protocols also have much longer scan ranges and often include the entire fetus, so that the contribution of both direct and scattered radiation is higher than from the pelvis examination. Our findings of estimated fetal dose levels differ a little bit from other reported values. Angel, Erin et al (Angel, o.a., 2008) present that for a typical abdominal and pelvic CT examination, the average fetal dose is approximately 24 mGy with a range of 16–31 mGy, depending on maternal size.

The results showed that CT-Expo gave the highest doses for the abdomen and other protocols independent of the trimester and that VirtualDoseCT gave the lowest doses for the third trimester and that SSDE gave the lowest dose for the second trimester. For the pelvis protocols the highest dose was estimated by SSDE and the lowest dose was estimated by VirtualDoseCT. However, all the methods estimated approximately the same dose, the maximum variation was 0.2 mGy and all the doses were low. CT-Expo may overestimate the dose since the phantom construction is simple and there is no possibility to adjust the phantom for either the patient size or a fetus size. A reasonable explanation is that the dose is distributed in a smaller phantom volume (non-pregnant uterus) which in that case overestimates the fetal dose compared to the reality where the dose is distributed over a bigger volume (fetus instead of non-pregnant uterus) and where the woman's belly is also larger than that of the phantom. CT-Expo takes into consideration approximately as many parameters as VirtualDoseCT but VirtualDoseCT can take into consideration the size of a pregnant woman in all the trimesters. $CTDI_{vol}$ and SSDE gave similar results, this may be because when using the SSDE method the conversion factor that is multiplied with the $CTDI_{vol}$ value is in many cases near 1 in this study. When comparing the bladder doses to the patient between CT-Expo and VirtualDoseCT there was quite a large difference. The bladder is an organ that does not vary in size depending on trimester, but CT-Expo estimated a much higher dose to the bladder than VirtualDoseCT, CT-Expo estimated 21 mGy and VirtualDoseCT estimated 10 mGy for the abdomen and other protocols. An explanation why CT-Expo estimated a higher dose may be that it does not take into consideration the patient's size during the different trimesters.

In common for all the methods is that the fetal dose estimates in the second trimesters was higher than those of the third trimester especially for VirtualDoseCT. This could depend on that the patients in the second trimester were larger than the patients in the third, which can be seen in Table 5, both for the visible patient circumference and for the LAT measures. $CTDI_{vol}$ was also higher for the patients in the second trimester which means that those patients have been scanned with a higher dose output level since the patients are larger and tube current modulation has been used. When using the SSDE method and taking into consideration the patient size the difference between the trimesters did not vary much at all, which also may be a result of that the patients in the second trimester are larger, the dose is then distributed in a larger volume and the average dose (SSDE) reduces. CODE and VirtualDoseCT do take the patient size into consideration, but the fetus size for both programs is smaller for the second trimester than in the third trimester. And taking into consideration that the patients in the second trimester received a higher $CTDI_{vol}$ means that a higher dose will be given to a smaller fetus phantom volume. In the third trimester the fetus size is larger but the $CTDI_{vol}$ was lower which means that a lower dose is distributed over a larger volume which gives a lower fetal dose.

The range of mean fetal absorbed dose estimated by different methods for the phantom was 6-10 mGy for the first trimester, 11-20 mGy for the second trimester and 14-25 mGy for the third trimester. The phantom study showed that CT-Expo estimated the highest value, VirtualDoseCT the lowest for the

third trimester, $CTDI_{vol}$ showed the lowest for the second and first trimester. Compared to the patient data, the exposure dose decreased in the third trimester and for the phantom the exposure dose increased. This confirms the results above that the patients in their second trimester was larger than the patients in their third trimester which affects the dose estimations. Since the phantom increased in size with each trimester and dose modulation was used, the CT gave a higher tube current over the larger phantom belly and the indicated $CTDI_{vol}$ increased and the fetal dose increased for all the estimation methods with increasing trimester.

VirtualDoseCT was the only program in this study that could estimate the dose to different parts of the fetus. It showed that the fetal skeleton receives the highest dose during a CT scan. The absorbed dose to the different parts of the fetus for the phantom scans in this study, was 8.2, 35.5 and 10.9 mGy for the second trimester and 8.61, 37.8 and 13.3 mGy for the third trimester respectively. Compared to Gu, Jianwei et al (Gu, Xu, Caracappa, & Liu, 2013), when they used tube current modulation the doses for the fetal brain, skeleton and soft tissue was 5.3, 22.8 and 6.9 mGy respectively during the second trimester and 12.7, 50.3 and 18.1 mGy respectively for the third trimester were close to our phantom study. However, some differences were seen due to different protocols used.

The SSDE results regarding the difference between the estimated fetal dose using the visible and approximate AP and LAT size showed that the estimated fetal dose using the visible size was a bit higher, but the difference was small, less than 1 mGy. This is reasonable since the visible size is smaller than the approximate size and the conversion factors is higher for the lower sums of AP and LAT. The difference was small because most of the time the patient was visible within the dFOV and if the patient was outside the dFOV, it was not by much, which makes the difference in AP and/or LAT small, making the difference in correction factor small. However, since patients are different in size there could be more extreme cases where the patient is further outside the dFOV in those cases the dose will differ more depending on which measurement method that is used.

For CODE when approximating the patient circumference to an ellipse or circle it showed that in all cases the approximation to an ellipse gave a better result than the approximation to a circle. The patient circumference was measured using the visible parts of the patient which means that in the cases where the patients were cut the circumference will be underestimated which entails that the dose will be overestimated. The worst overestimation will be when both the AP and LAT are cut. The dose will be overestimated because the same average dose is distributed over a smaller volume.

For the phantom measurement using the abdomen protocol the difference in dose between using the specific CT slice tube current or mean tube current is noticeable. As can be seen in Table 7 the DLP when using the tube current for the specific CT slice was much higher than the DLP for the examination which means that the dose is overestimated when using the tube current for the specific CT slice. Using the specific CT slice tube current gave the fetal dose 9.8 mGy compared to 9.2 mGy when using the mean tube current for the first trimester. For the second trimester the fetal doses were 22.5 and 16.9 mGy respectively and for the third trimester the doses were 27.9 and 21.8 mGy respectively. The tube current for the specific CT slice overestimates the dose quite a bit as can be seen in the dose values.

Considering the fetal dose limit of 100-200 mGy none of the patients were near this threshold for these examinations. The total dose to the fetus where highest during the abdomen protocols indicating that this is the group of patients that needs to be more careful about. For single CT abdomen examination with the dose levels in this study there is not a risk that the threshold may be exceeded. But if the patient should undergo several different abdomen scans there should be an awareness of the accumulated dose to the fetus. For the pelvic protocols the dose level is very low compared to the threshold.

The different fetal dose estimation methods in this study have different advantages and disadvantages. SSDE is a simple method with few parameters, the method only takes into consideration the $CTDI_{vol}$ and the patient's size in the AP and LAT dimensions. According to AAPM (AAPM246, 2019) SSDE is capable of estimating a fetal dose when the entire fetus is irradiated, in cases where only parts of the fetus is irradiated SSDE serves as an upper limit of the fetal dose. This becomes a source of error in the pelvis protocols where only half the pregnant woman's belly is within the dFOV. For CODE the choices for tube voltages are limited and the tube voltages in these cases need to be approximated which induces some errors. The results are given with 3 decimal accuracy, which seems like an unreasonably high accuracy. The maximum scan range in the superior direction is 50 cm, just above the shoulders in CODEs phantom which in most cases works well since the program is designed to estimate fetus doses, but there might be cases (1 in this study) in which the scan range is longer than that. In those cases, the phantom anatomy is limited which means that the dose will be underestimated since there will be missed scattered radiation, but this is a very small contribution. For VirtualDoseCT, there are a lot of CT manufacturer choices, but the list is unfortunately not updated so newer CT scanner models are not available which can affect the result. This was the case in this study with the anthropomorphic phantom measurements that were scanned on a GE revolution CT as well as the patients that were scanned on a Siemens Force CT scanner (3 patients). The phantom measurement was estimated using the GE Discovery CT 750 HD scanner model in VirtualDoseCT which induces some errors in the results. The patients that were scanned on the Siemens Force CT scanner were not included in the VirtualDoseCT fetal dose estimation.

One source of error in the fetal dose estimates is to try to match the total scan length and the included organs with the phantoms of the softwares. To consider both these factors at the same time proved hard to do in some cases, and in those cases the scan length was prioritized, this is therefore a source of error in this study. While performing these methods the goal was to use geometric size measured in the part of the woman/phantom that was the widest and would give one of the highest tube currents for the examination, but since it is a visual judgement the estimation has some margin of error due to the individual judgement. Looking through the patients' CT images it showed that the AP measure is constant over 1-3 cm of the widest part of the belly, which means that the dose estimation will not be affected if the viewer is calculating the dose based on images within this interval. The LAT dimension varied even less. This affects the methods that involve the patient size and circumference such as SSDE and CODE.

The user friendliness of the dose estimation methods is quite different. $CTDI_{vol}$ is the easiest one since it is often displayed for every CT examination. SSDE is a quick and easy method for estimating the fetal dose. It does not require much information and the information that is required could easily be found in the images for the CT examination. CT-Expo is also a quite user-friendly program with straightforward inputs that are numbered in the order that you are supposed to enter them. It does require more inputs which mostly can be found in the DICOM information, but to acquire an adjusted tube current for the examination to fit the DLP, the tube current is advantageously adjusted strategically within the program. CODE is a very straightforward and simple program to use, but it requires inputs of $CTDI_{W}$ per 100 mAs and $CTDI_{Free\ in\ air}$ per 100 mAs which must be measured or calculated from the technical reference manual at the CT specific conditions such as the used tube voltage and collimation. The program offers a very specific trimester division and requires patient specific inputs such as patient circumference and in the early trimesters, the fetus depth, which may contribute to a more specific fetal dose estimation. The phantom in CODE is more advanced than CT-Expo which also may contribute to a more specific fetal dose estimation. VirtualDoseCT is quite user-friendly program with many parameter inputs. It is important to enter the parameters in the order that they are standing (left to right) so that some autogenerated values appear. Its CT manufacturer list is not updated which means that in some cases a suitable replacement CT need to be found for the calculation which is not always easy. It also requires $CTDI_{W}$ per 100 mAs which must be measured or found in specifications. To some extent, this input may be able to compensate for the cases where the "wrong" CT scanner are chosen. The VirtualDoseCT phantom is more advanced than CT-Expo and

has options for a 3-, 6- or 9-months pregnant woman and the size of the fetus changes with the trimester which should give a more accurate fetal dose estimation. It also estimated the absorbed dose to different parts of the fetus and mother simultaneously which could be of interest.

6 Conclusion

In conclusion the abdomen protocols give about 15 times higher fetal dose than the pelvic protocols. The estimated fetal doses using the different estimation methods are similar, which may conclude that for single examinations it does not matter which method is used to estimate the fetal dose since the dose levels are much lower than the threshold value. But for repeated examinations, methods such as CODE or VirtualDoseCT may want to be used since they can represent the real-life circumstances better. CT-Expo tends to estimate higher doses for the second and third trimesters compared to the other methods. CT-Expo seems to be a less accurate tool for estimating a fetal doses in later trimesters. VirtualDoseCT is similar in complexity to use compared to CT-Expo and CODE but it is not very updated regarding choices of CT scanners.

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