

Comparing different methods for estimating radiation dose to the conceptus

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Abstract

Purpose To compare different methods available in the literature for estimating radiation dose to the conceptus ($D_{\text{conceptus}}$) against a patient-specific Monte Carlo (MC) simulation and a commercial software package (CSP).

Method Eight voxel models from abdominopelvic CT exams of pregnant patients were generated. $D_{\text{conceptus}}$ was calculated with an MC framework including patient-specific longitudinal tube current modulation (TCM). For the same patients, dose to the uterus, D_{uterus} , was calculated as an alternative for $D_{\text{conceptus}}$, with a CSP that uses a standard-size, non-pregnant phantom and a generic TCM curve. The percentage error between D_{uterus} and $D_{\text{conceptus}}$ was studied. Dose to the conceptus and percent error with respect to $D_{\text{conceptus}}$ was also estimated for three methods in the literature.

Results The percentage error ranged from -15.9% to 40.0% when comparing MC to CSP. When comparing the TCM profiles with the generic TCM profile from the CSP, differences were observed due to patient habitus and conceptus position. For the other methods, the percentage error ranged from -30.1% to 13.5% but applicability was limited.

Conclusions Estimating an accurate $D_{\text{conceptus}}$ requires a patient-specific approach that the CSP investigated cannot

provide. Available methods in the literature can provide a better estimation if applicable to patient-specific cases.

Key Points

- A patient's internal anatomy affects the dose to the conceptus.
- Conceptus position has an influence on its dose estimation.
- Patient anatomy and specific TCM must be considered for accurate conceptus dosimetry.
- D_{uterus} to a standard-size phantom should not be used as $D_{\text{conceptus}}$.

Keywords Pregnancy · Dose to the conceptus · Tube current modulation · Commercial software package · Monte Carlo simulations

Abbreviations

CT	Computed tomography
MC	Monte Carlo
TCM	Tube current modulation
CPS	Commercial software package
LAT	Lateral diameter
AP	Anterior-posterior diameter
ED	Effective diameter
$D_{\text{conceptus}}$	Dose to the conceptus
D_{uterus}	Dose to the uterus

Introduction

Recent data published by Woussen et al. showed an increase of CT examinations in pregnant women at one institution, with 3–4 pregnant patients getting a CT scan per year from 2008–2011, to 7–11 patients per year from 2012–2014 [1]. This study confirms what had been published earlier by Lazarus [2], who

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reported a yearly increase in imaging in the pregnant population.

Although it is preferable to perform a non-X-ray examination on pregnant women if the same information can be obtained, CT should be still used when there is a specific clinical need. A major concern arises when the conceptus is directly irradiated, and therefore the examination has to be essential for life saving or well justified [3]. There are existing guidelines that suggest screening for pregnancy before performing an examination with ionizing radiation in order to minimize the number of unexpected exposures [4]. Radiation doses can be reduced if the proper technique is used. Major impact is from the use of low-dose protocols, a reduced scan range, low tube current, use of tube current modulation, and an increased pitch in comparison to the standard protocols [5].

Nowadays, the concern about radiation dose to the conceptus is of great interest, as it allows radiation risks be taken into account when performing risk-benefit analyses and permits potential embryo risks to be managed in an appropriate manner [6].

As it is not possible to measure the radiation dose to the conceptus directly, different methods have been developed in the past, where simplified assumptions are used [7]. The simplest approach for early pregnancy patients is to calculate dose to the uterus in a non-pregnant phantom [8]. More advanced methods account for maternal body size and estimates $D_{\text{conceptus}}$, for example, by placing dosimeters in anthropomorphic phantoms [8–14] or by using mathematical [15] and realistic computational phantoms in Monte Carlo simulations [7, 16–18]. However, there are still some limitations to these approaches, as some of these studies were performed with fixed tube current [7, 15, 16], whereas nowadays tube current modulation (TCM) is used in almost all examinations. Moreover, anthropomorphic phantoms cannot account for an accurate estimation of fetal or maternal body size.

While Monte Carlo simulations remain the gold standard for dose estimations, the complexity to develop a dosimetry framework, the computational time and/or the difficulty to create each specific computational model for every patient, prevent this method to be implemented in clinical routine and is mainly used for research purposes only.

Instead, commercial software packages (CSP) are more accessible to health institutions and, therefore, often used for $D_{\text{conceptus}}$ estimation, even knowing the limitation of such calculation, which often does not account for maternal body size or the presence of the conceptus.

The purpose of the present study was to compare the dose to the conceptus ($D_{\text{conceptus}}$) estimated using patient-specific Monte Carlo simulations against the results obtained using a CSP and available methods in the literature.

Materials and method

Patient data collection

For this study, a subgroup of patients in a database containing pregnant patients from January 2008 to September 2014, was used [1]. This subgroup consisted of eight abdominopelvic scans, all of them clinically indicated. The population included two patients in the first trimester of pregnancy, four in the second, and two in the third trimester. Average gestational age was 20 weeks (6–31 weeks). Average patient age was 25 years (19–31 years). Gestational age was defined with respect to the last menstruation.

Among the eight patients, one had a CT scan that did not fully cover the uterus and, therefore, the fetus. This patient belonged to the second trimester patients. The database was then reduced to seven patients.

A description of the patient characteristics and the scan indications of the CT examinations are presented in Table 1.

To assess the patient size, the geometric lateral (LAT) and anterior-posterior (AP) diameters were measured at the middle of the gestational sac or fetus, when visible. The effective diameter (ED) was calculated as described in the AAPM Report 204 [19]. Water equivalent diameters (WED) were not estimated but it has been shown in literature that for the CT scans from the abdominopelvic region, WED, and ED match better than for thorax examinations [20].

Scan parameters

The patients were scanned with two different CT scanners, Siemens Somatom Sensation 64 and Siemens Somatom Definition Flash (Forchheim, Germany), and with different kVp: 100, 120, and 140, due to the different types of examinations. The absence of a standardized protocol for pregnant patients and the fact that in some cases the pregnancy was not known explains some of the variability in scanning parameters. Moreover, there was a large range of clinical indications. All the examinations were performed with tube current modulation, the slice thickness varied from 1.5 mm to 5 mm; the pitch varied between 0.6 and 1.2.

Voxel models

The voxel models of the maternal and fetal anatomy were created from the CT images using ImageJ (version 1.48 x Java 1.6, National Institutes of Health, USA) and the organs segmentation was performed by a radiologist. According to the ICRP report 89 [21], organs to be differentiated for radiation-induced risk estimates in cases of pregnancy are amniotic fluid, placenta, fetus, and uterus. We could differentiate between uterus and gestational sac for the first trimester patients, and uterus, placenta, and fetus for later gestational ages.

Table 1 Patients characteristics and scan indications of the CT examinations. GA = gestational age

Model	Maternal age (years)	GA (weeks-days)	Trimester	Perimeter (cm)	kVp	mAs/ref	Indication
1*	24	6	First	109.2	120	141/180	Crohn's disease
2*	25	12-6	First	110.9	140	319/161	Polytrauma
3	22	17	Second	102.9	100	330/275	Fetal dysplasia
4†*	19	17-6	Second	95.1	140	188/350	Lower back pain
5	26	23-4	Second	85.6	120	65/100	Fetal dysplasia
6	31	24-1	Second	118.0	100	291/275	Fetal dysplasia
7	24	29-6	Third	96.2	120	171/200	Polytrauma
8	30	31-3	Third	107.9	100	241/275	Fetal Dysplasia

† Patients with fetus not fully covered in the scan range

* Unknown pregnancy

The voxels inside the gestational sac were modelled as water. For the second and third trimester patients, all the tissue within the uterine wall, except for the fetus and placenta, was considered to be uterine mass. When visible, voxels within the fetus were modelled as soft tissue, bone, and brain. Fetal bones were segmented using a semi-automated tool, while the soft tissue and brain were segmented manually based on the anatomy of the fetal skeleton.

For the voxels associated with the mother, ten different tissues were segmented: air inside the body, urinary bladder, breasts (when included in the CT scan), bones, soft tissue, kidneys, liver, lung, muscle, and skin. The urinary bladder and breast tissue were segmented manually, and similar to the uterus, differentiation between urinary bladder content and urinary bladder wall could not be made due to poor image contrast. All other organs were segmented using semi-automated selection tools. An example of a segmented image is shown in Fig. 1.

The voxel models corresponded only to the anatomical region visible from the CT images, so the regions corresponding to the over-ranging due to the helical scan were not included. When the voxel model was finished, the images were subsampled from a 512x512 matrix to a 256x256 matrix in order to reduce the simulation time.

A second version of the fetus from the second and third trimester patients was created by assigning all the voxels as soft tissue to have a description of a homogeneous conceptus.

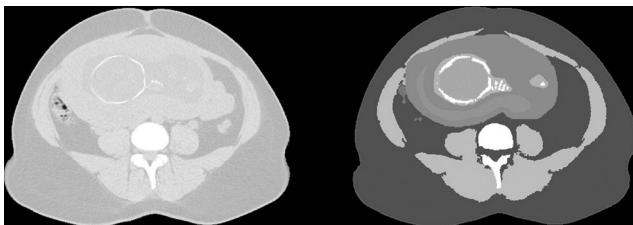


Fig. 1 Creation of a voxelized patient model from the original CT image. From left to right: the original CT image, the segmented uterus, and the resulting voxelized patient model

The tissue compositions in the voxel models were derived from reference values in the Handbook of Anatomical Models for Radiation Dosimetry, and were based on the ICRU 44 and ICRP 37 [22].

Monte Carlo simulations

A previously validated Monte Carlo simulation framework [23] for patient specific dosimetry using EGSnrc (version 4-2.4.0; Electron Gamma Shower, National Research Council, Canada) was used and modified to allow for the different kVs of the scanning protocols. The simulation framework accounts for the rotational geometry of the scanner, the bowtie filter, and TCM. Further details about the simulation framework can be found in Lopez-Rendon et al. [23]. Initially this framework was only for a Siemens Definition Flash, and it was validated only for 120 kV and the body bowtie filter as implemented on that scanner. For the purpose of present dose calculations we validated the framework for different kV and the same bowtie filter using dose measurements in CTDI phantoms with an ionization chamber. As our database of patients included also patients scanned in a Siemens Sensation 64 scanner, the characterization of the bowtie filter of that scanner was performed in order to adjust our simulation framework. The validation of the modified simulation framework for this case was also performed with dose measurements in CTDI phantoms and using an ionization chamber.

All CT scans were simulated as clinically acquired, with the corresponding kV, pitch, and each specific longitudinal tube current modulation profile for each voxel model; combined transverse and longitudinal 3D modulation information was not available as this information is proprietary of manufacturers. This longitudinal modulation was extracted from the DICOM headers and was numerically normalized against the average mA across the entire scan. In order to account for the longitudinal modulation in the Monte Carlo framework, the associated energy deposition for each projection when

calculating the dose integral was scaled by an extra weighting factor which is based on information associated with the tube current modulation. An example of the TCM curves of three patients is shown in Fig. 2. All the simulations were performed with 50 to 100 million simulated X-rays photons.

Dose calculations with Monte Carlo

The dose to the conceptus was calculated with the MC framework as follows: for the first trimester patients, the dose to the conceptus was equivalent to the gestational sac dose, as that was the only organ related to the fetus that could be visible from the CT images. For the second and third trimester patients, the dose to the fetus was considered the mass weighted average dose of the organs which composed the fetus and were segmented for each model, namely the bones, the soft tissue, and brain, as described earlier. The absorbed dose to the conceptus was calculated following Eq. 1:

$$D_{conceptus} = \frac{D_{tissue_1} * m_{tissue_1} + D_{tissue_2} * m_{tissue_2} + \dots + D_{tissue_n} * m_{tissue_n}}{\sum_1^n m_{tissue}} \quad (1)$$

where D_{tissue} is the dose associated with the corresponding tissue, and m_{tissue} is the mass of the corresponding tissue.

An estimation of a homogenous conceptus (only soft tissue) was also performed. The results of the Monte Carlo simulations were compared with the results of a detailed voxelization of the conceptus versus a soft tissue conceptus only.

Dose calculations with CT-Expo

In our previous study [1], the dose to the uterus for each of the patients in this database was calculated with commercial software: CT-Expo v.2.2. The female adult phantom, EVA, is used in this package, and it cannot be adjusted for body size. This phantom has an anterior-posterior size of 18.8 cm [24] and an estimated perimeter of 93 cm [7]. From that anterior-posterior size we can assume an ED of 23.0 cm according to AAPM

Report 204 [19]. A generic TCM as implemented in this software was used and the dose to the uterus was considered equivalent to the dose to the conceptus. The TCM profile from CT-Expo was obtained by evaluating measured attenuation data of female adult standard patients scanned with CareDose4D from Siemens (Forchheim, Germany) [24].

The results from the MC framework ($D_{conceptus}$) were compared with the results calculated with CT-Expo v. 2.2 (D_{uterus}) used in the previous study [1] by calculating the percentage error as in Eq. 2.

$$\% \text{ error} = \frac{(D_{uterus} - D_{conceptus})}{D_{conceptus}} * 100 \quad (2)$$

where the D_{uterus} is the dose calculated with CT-Expo and $D_{conceptus}$ is the dose calculated with the Monte Carlo simulations.

A visual comparison of the patient-specific TCM and the generic TCM included in CT-Expo for the female phantom was performed by plotting both TCM profiles on a coronal image from each patient.

Dose calculation with available methods in literature

There are three manuscripts in the literature that describe methods to estimate the dose to the conceptus. The first work is the one by Angel et al. [7], where three different approaches are described: one based on a general approximation ($D_{a,ave}$) of 10.8 mGy/100 mAs; the other two are based on a correlation between the dose to the conceptus and the patient perimeter ($D_{a,perim}$) or the patient perimeter plus the conceptus depth ($D_{a,fetal}$), respectively.

The second is proposed by Damilakis et al., and combines normalized conceptus dose coefficients with CTDI free in air measurements to obtain the dose to the conceptus for all gestational ages (D_b) [15].

The third paper was also published by Damilakis et al. Here the authors predict dose to the conceptus from abdominal CT scans only for pregnant patients during the first weeks of gestation (D_c) [18].

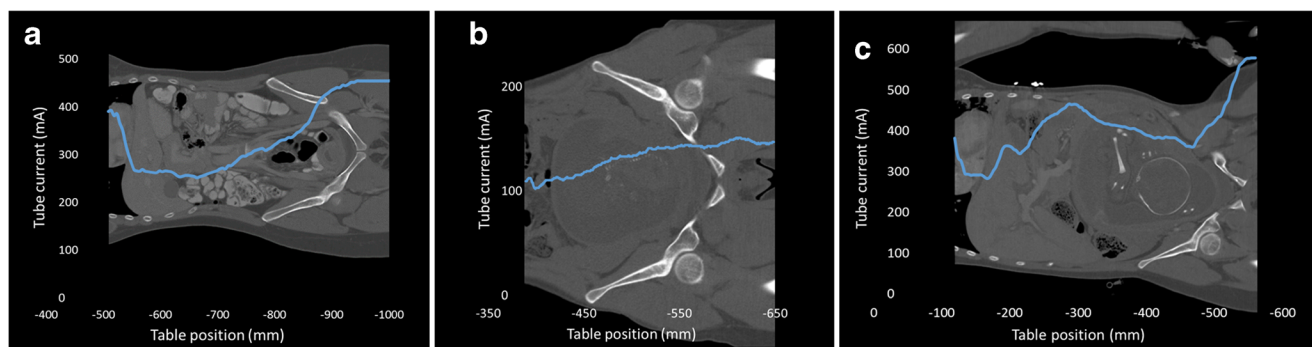


Fig. 2 Tube current modulation as a function of the table position on coronal images of three patients, each from each trimester A: first, B: second, and C: third trimester

In the present study, the dose to the conceptus was calculated with all these methods when applicable, as some of them were developed for specific conditions in terms of beam quality or scanner model. The percentage error as described before was also calculated for each method respect to our Monte Carlo results.

Results

The modified simulation frameworks were validated and for the Siemens Sensation 64 at 120 kV the percent error between the simulations and measurements was between -3.4 and 5.3 % with an average error of 2.5 %. For the Siemens Definition Flash at 100 kV the percent error between the simulations and the measurements was between -3.3 and 4.6 %, with an average error of 1.3 %, and at 140 kV the percent error was between -1.9 and 3.6 %, with an average error of 1.8 %.

In Table 2, the results between the calculation from CT-Expo (D_{uterus}) and the Monte Carlo framework ($D_{\text{conceptus}}$) are presented along with the other methods available from literature ($D_{\text{a,ave}}$, $D_{\text{a,perim}}$, $D_{\text{a,fetal}}$, D_{b} , D_{c}). It can be seen that in our patient group, patient size has no correlation to gestational age. For example, the 6 weeks pregnant patient had bigger ED (29.8 cm) than the 29 weeks pregnant patient (27.2 cm). The smallest difference between CT-Expo and Monte Carlo simulations are for model 5, who had the smallest ED. CT-Expo provided the largest percentage error range, from -15.9 % to 40.0 %. From all the available methods in the literature, the percentage error ranged from -30.1 % to 13.5 %, which is indeed a smaller range than with CT-Expo, and the smallest percentage error was found for D_{b} , from -29.4 to -8.9.

By comparing the effects of a detailed description of the conceptus versus a conceptus consisting only of soft tissue, a maximum underestimation of -9.4 % was found for one of the 3rd trimester patients. A tendency for a larger underestimation as a function of the gestational age is suggested (Table 3), though this should not be concluded at this point as some of the patients were scanned for fetal dysplasia.

When comparing the TCM profiles from each of the pregnant models with the generic TCM profile from CT-Expo (Fig. 3), differences are observed due to patient habitus and fetus position. The first two models are from the first trimester, but the patient-specific TCM values are changing in the opposite direction at the level of the conceptus in comparison to the generic TCM from CT-Expo due to the internal anatomy of the patients. As an example, the bladder is full in Model 2, which pushes the gestational sac in a higher position than in Model 1.

Discussion

The purpose of this study was to compare the dose to the conceptus estimated with Monte Carlo simulations, where

the effects of maternal body size and patient-specific TCM were taken into account, with the results obtained with a CSP using a non-pregnant, non-resizable anthropomorphic mathematical phantom, and with the three methods available in the literature.

The results showed that CT-Expo under- and overestimated the dose to the conceptus, from -15.9 % to 40 %, depending on patient anatomy and patient-specific TCM. For the 1st trimester models, one underestimation and one overestimation were found; anatomy and the specific TCM were determining for the doses (Fig. 3). In particular, one of the models (Model 2) had a filled bladder, which affected the fetal position and has, therefore, an effect on the conceptus dose. In Model 1 on the contrary, the position of the gestational sac was lower and closer to bone structures. The depth of the conceptus in the abdomen of a patient is influenced by the bladder volume and this will impact the dose to the conceptus [10]. If an accurate estimate of the absorbed dose to the conceptus is needed the embryo depth has to be taken into account [25]. Assuming a fixed position for the conceptus, as is the case when estimating dose to the uterus from a standard phantom can lead to errors, as we can see in Table 2. Patient specific Monte Carlo intrinsically accounts for all effects of position.

Ideally one would think that it is possible to estimate D_{uterus} as a surrogate of $D_{\text{conceptus}}$ for an early pregnant patient, if the patient's size is similar to the anthropomorphic phantom of the commercial software used. However, our study shows that even for those patients, differences in dose can be found due to patient-specific TCM. Indeed, as the commercial software includes a generic TCM, the true effects of TCM are not always correctly accounted for, as illustrated in Models 1 and 2 in this study. Moreover, in our database the first trimester patients had a larger ED than the anthropomorphic phantom (smallest ED was 29.7 cm versus 23 cm of the phantom).

There are some methodologies that have been developed to assess dose to the conceptus for different patient sizes [7, 15, 18] and conceptus depth; however, their applicability is limited to specific conditions, e.g. beam energy and scanner model. It can be seen from Table 2 that Angel's method, with the two variable equation ($D_{\text{a,fetal}}$), provided smaller errors than CT-Expo when compared to our Monte Carlo data. Damilakis' method (D_{b}) [15] provided the smallest error in comparison to CT-Expo, from -29.4 to -8.9 %, but, again, it was not possible to apply it to all the cases in our study as it was developed for specific scanners, which start to be obsolete. This suggests that there is a need to update these methods for more recent scanners as well as for a broader range of kV.

Finally, the last method of Damilakis [18] was meant for early pregnancy, up to 7 weeks, with the dose to the conceptus assumed to be the dose to the uterus. The method could only be applied to one of our cases.

When comparing the doses for the different trimesters at the same kV (120), all acquired with the same CT scanner, it is

Table 2 Radiation dose to the conceptus for the eight voxel models including the gestational age and effective diameter (ED). $D_{conceptus}$ was estimated with the Monte Carlo framework, D_{uterus} was estimated with CT-Expo, and $D_{a,ave}$, $D_{a,perim}$, $D_{a,fetal}$, D_b , and D_c with available methods found in the literature. The percentage error is presented considering the $D_{conceptus}$ as the gold standard method

Model	GA (weeks-days)	ED (cm)	kV	$D_{conceptus}$ (mGy)	D_{uterus} (mGy)	% error D_{uterus} $D_{conceptus}$	$D_{a,ave}$ (mGy)	%error $D_{a,ave}$ $D_{conceptus}$	$D_{a,perim}$ (mGy)	%error $D_{a,perim}$ $D_{conceptus}$	$D_{a,fetal}$ (mGy)	% error $D_{a,fetal}$ $D_{conceptus}$	D_b (mGy)	% error D_b $D_{conceptus}$	D_c (mGy)	% error D_c $D_{conceptus}$
1	6	29.8	120	18.6	15.7	-15.6	12.7	-31.8	11.5	-38.2	13.4	-28.0	14.3	-23.1	13.0	-30.1
2	12-6	29.7	140	45.1	55.1	22.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	17	28.9	100	14.2	18.8	32.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
5	23-4	26	120	7.9	6.7	-15.2	7.0	-11.1	7.5	-5.1	8.5	7.6	7.2	-8.9	NA	NA
6	24-1	34.3	100	12.5	17.5	40.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
7	29-6	27.2	120	24.9	20.6	-15.9	15.4	-37.2	16.2	-33.9	27.8	13.5	17.3	-29.4	NA	NA
8	31-3	30.4	100	12.9	18	39.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

$D_{conceptus}$, Dose to the conceptus estimated our Monte Carlo simulation

D_{uterus} , Dose to the uterus calculated with CT-Expo

$D_{a,ave}$, Obtained with the mean value of 10.8 mGy/100 mAs developed by Angel [7]

$D_{a,perim}$, Obtained with the results derived with one parameter (perimeter) equation developed by Angel [7]

$D_{a,fetal}$, Obtained with the two variable equation (perimeter and fetal depth) developed by Angel [7]

D_b , Obtained with method based on body size, beam width and scanned length developed by Damilakis [15]

D_c , Obtained with method for the first seven weeks developed by Damilakis [18]

NA, Not available as the method did not allow calculating for that specific case

Table 3 Percentage difference between the dose to the conceptus from a detailed voxelization of the conceptus versus a soft tissue conceptus

Model	Trimester	kV	Detailed fetus	Soft tissue fetus	% difference
3	2nd	100	14.2	13.6	-4.2
5	2nd	120	7.9	7.6	-3.8
6	2nd	100	12.5	11.5	-8.0
7	3rd	120	24.5	22.2	-9.4
8	3rd	100	12.9	12.1	-6.2

not surprising that the dose to the third trimester model increases. Hence, TCM in 3rd generation scanners increases the dose for larger amount of soft tissue in late pregnancy [13]. As a result, the $D_{conceptus}$ for the first trimester patient was higher than the dose in the second trimester patient, as the mAs used for the first trimester was higher (Fig. 2) and the patient size is one of the biggest (Table 2), confirming the importance of body habitus. A recent paper by Solomou [14] showed that AEC reduces conceptus radiation dose at all gestational ages. This finding was based on work with an anthropomorphic phantom representing the average pregnant patient for each trimester having a continuously increasing perimeter. The paper showed that the mean mAs value decreased when compared to fixed mAs, but the reduction is lower as the gestational age increases. In our study, body habitus is not necessarily increasing with gestation age and this will drive TCM accordingly.

Because of pregnancy, a larger effective diameter is expected at later gestational ages, and therefore, big differences in the anatomy between a pregnant patient and non-pregnant anthropomorphic phantoms should lead to larger differences in the dose calculations for patient in the latest trimester. However, in our database, patients from earlier gestational age had bigger ED than later gestational age models, and the smallest error was for the patient who had similar size as the anthropomorphic phantom. Therefore, if an accurate $D_{conceptus}$ is needed, a precise calculation with all the parameters which influence the dose, namely patients size, internal anatomy, fetus position and patient specific TCM, should be taken into account.

There were some limitations in this study. First, the voxel models of the pregnant patients were not complete as they were created from the CT images. In some cases the FOV was small to include the whole patient and a part of the hips was cut. Second, as all the CT scans were performed in a helical mode, the effects of over-ranging were present, but the anatomical region at the place of over-ranging was not included as the voxel phantoms created were from the CT images. Third, when estimating dose to the uterus from stylized phantoms or even fixed phantom models, accuracy of the dose is limited by the error associated with the depth of the conceptus. The effect of bladder volume can be important [25]. Finally, we only have two or three models per trimester, although it is visible even from this small sample that body habitus varies considerably among the population.

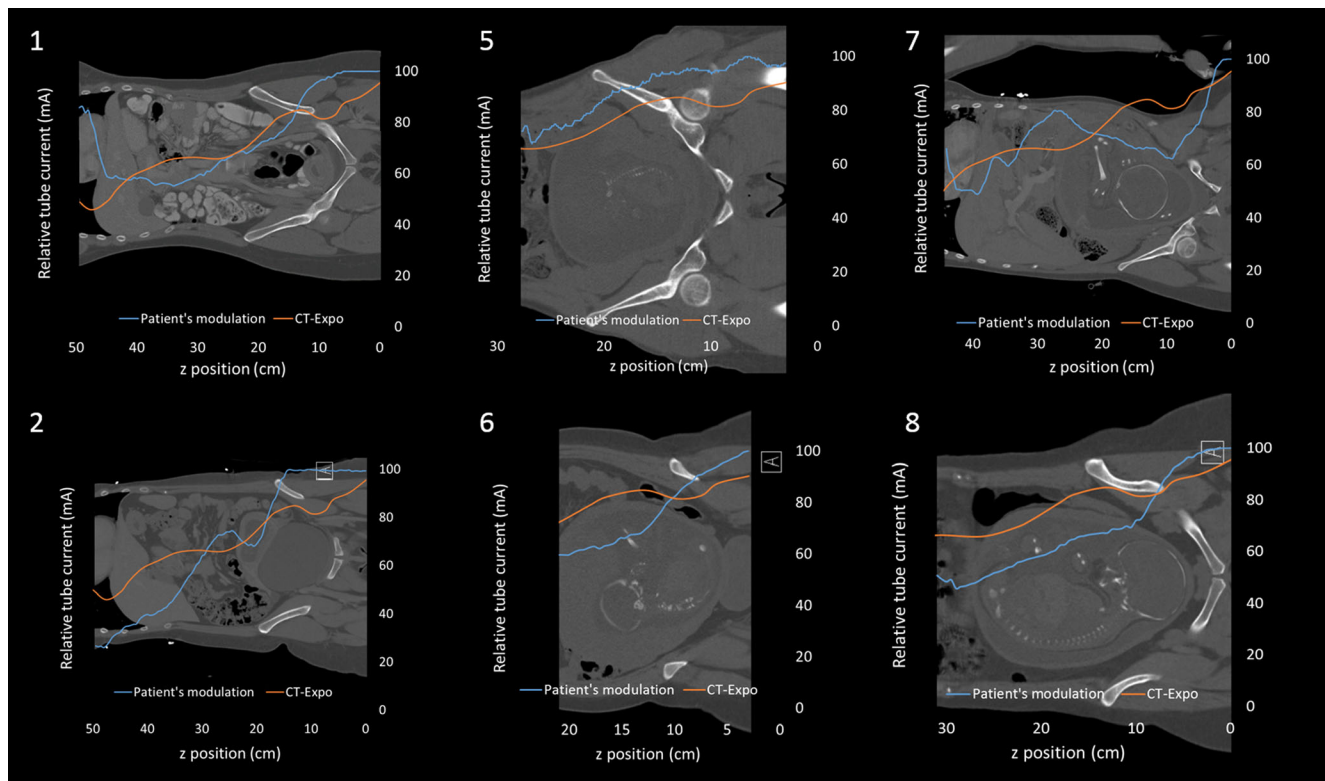


Fig. 3 Comparison of the patient-specific TCM profile (blue) and EVA's TCM profile (orange) from CT-Expo for six patients from our database

In conclusion, estimating dose to the conceptus is not a straightforward task as there are many parameters that need to be taken into account if an accurate estimation is the goal. From our results it can be appreciated that patient size (and not only gestational age), internal anatomy, position of the gestational sac or fetus, position of the bladder, and TCM have a substantial impact on dose. CPS using a (non-pregnant) standard-phantom and generic TCM should be used with caution as already in our limited study with CT-Expo on seven cases, dose deviations were up to 40 %. It must be stated that the CT-Expo has a disclaimer regarding its use on calculating dose to individual patients. The three methods found in literature can provide a better estimation but are limited when different scan parameters are used in patient scans. However, it is recommended to use them when possible, instead of CT-Expo, if a better accuracy is desired.

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