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RESEARCH ARTICLE

MEDICAL PHYSICS

Absorbed dose differences between twin fetuses for pregnancy patients in CT examinations

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Abstract

Background: Estimation of the radiation dose to the fetus is essential for the assessment of radiation risks and benefits to pregnant patients undergoing radiological examinations. During the past decade, the global twinning rate has soared resulting from embryo assistance and increased delivery age. However, to the best of our knowledge, radiation dosimetry in multiple pregnancies from radiological imaging has never been reported before.

Purpose: The purpose of this study is to develop personalized computational models for twin fetuses based on clinical CT images of real pregnant patients and to estimate personalized radiation doses for twin fetuses from abdominal/pelvic CT examinations.

Methods: Personalized computational phantoms representing pregnant females with twins at the second and third trimesters were constructed based on CT images of two pregnant patients. Monte Carlo calculations were performed using the MCNP transport code and three validated CT scanners to estimate the radiation dose of twin fetuses during abdominal and pelvic CT examinations.

Results: The absorbed fetal organ dose was calculated and compared between twins. For the same patient, the absolute difference in fetal organ dose between twins varies between 0.63% and 39.64% with an average value of 12.85%. The estimated total-body dose differences for twin fetuses were 11.55% and 7.51%, respectively, for pregnant patients at 22 and 30 weeks gestational age.

Conclusion: The variations of body weight and organ mass affect the absorbed dose of twin fetuses. Personalized computational models provide more accurate fetal radiation dosimetry estimates for pregnant patients with twins. This work also contributes to a better understanding of model-induced uncertainties in external radiation dosimetry for the developing fetus.

KEYWORDS
computational phantom, radiation dose, twin fetuses, x-ray CT

1 | INTRODUCTION

In the past decade, the number of pregnant patients undergoing CT screening has increased by 25% annually while the radiation risks to the fetus from diagnostic radiological imaging have attracted a great deal of public attention.[1,2] The developing embryo/fetus presents a significantly higher radio sensitivity than adults.[3] The ICRP reports a threshold radiation dose of 100 mGy for deterministic effects occurring on the fetus, such as malformation, death, and mental retardation.[4] In the meantime, ionizing radiation exposure to the fetus may also result in hazardous effects, such as gene mutation, mental retardation, organ deformity, childhood cancer, and abortion.[5] In clinical practice, justification for the fetal dose requires accurate estimation of the risk-benefit for the pregnant patient from diagnostic radiological examinations.[6] The calculation of fetal radiation dose for each individual case is a multidisciplinary

Abbreviations: CT, computed tomography; HU, Hounsfield unit; ICRP, International Commission on Radiological Protection; NURBS, Non-Uniform Rational B-Splines; WHO, World Health Organization.

challenge requiring the involvement of radiologists and medical physicists. Computational phantoms of pregnant females have been developed and combined with Monte Carlo simulations for fetal radiation dosimetry calculations.[7] Gu et al.[8–10] estimated the fetal dose to pregnant patients from the chest, kidney, and abdominal CT examinations using three pregnant computational phantoms. Motavalli et al.[11] reported the fetal dose in pulmonary angiography based on a set of pregnant female phantoms at 3-, 6-, and 9-months gestation periods.[12] Hardy et al.[13] generated a set of reference data for fetal doses using Monte Carlo simulations. Xie et al.[14] developed a method to register reference pregnant phantoms to match patients' CT images and provided a series of mathematical formulations for fetal dose estimation from CT scans.[15] For personalized radiation dosimetry, Angel et al.[16] constructed patient-specific voxel models and reported a schema for calculating fetal radiation dose from abdominal CT examinations.

Advances in healthcare stimulated the emergence of assisted reproductive technology which became very popular. The global twinning rate has soared worldwide[17] owing to the application of embryonic assistance and the extension of the childbearing age.[18,19] The volume, position, and anatomical characteristics of twin fetuses present significant differences from those of singletons which tend to be weightier and bigger at the same gestational age. However, to the best of our knowledge, computational models of pregnant females with twin fetuses has been rarely reported. So far, only Xie et al.[20] constructed a hybrid twins model for radiation dosimetry studies of pregnant patients in nuclear medicine. In this context, the purpose of this study is to develop personalized computational models for twin fetuses based on clinical CT images of real pregnant patients and to estimate personalized radiation doses for twin fetuses from abdominal/pelvic CT examinations. We also calculated the organ-level absorbed doses to individual twin fetuses and compared the dosimetric aspects between twin fetuses in the same conceptus using MC calculations, which were further compared with results reported in established singleton pregnancy research.

2 | MATERIALS AND METHODS

2.1 | Personalized models for twin fetuses

This study used CT images of two pregnant patients with twins undergoing abdominal and pelvic CT examinations at Geneva University Hospital. The gestational ages of patients at examination time are 22 weeks at the second trimester and 30 weeks at the third trimester, respectively. The ages of the two patients were 33-years and 26-years, respectively. The maternal contour, skeleton, kidney, uterus, placenta, fetal contour, fetal skeleton, and fetal brain were manually segmented based on CT images as shown in Figure 1 where the contours of the two fetuses of the twins are represented in different colors (purple and yellow). The identified organs and tissues were reconstructed as polygon mesh models and imported into 3D modeling software for further processing. The NURBS model of fetal organs was constructed from the polygon mesh model using the lofting method implemented in the Rhinoceros software. The fetal skeleton was further divided into skull, spine, ribs, clavicle, scapula, humerus, ulna, radius, hand bone, hip, femur, fibula, tibia, and foot bone. The fetal spinal cord was constructed as a pipeline model inside the spine. Other fetal organs were scaled from the corresponding organs of the "Anchor" model constructed in previous work by our group.[21] The organ scaling factor was calculated as the ratio of the skull volume of the fetal phantom to be constructed and the skull volume of the Anchor phantom. After organ scaling, the fetal organs were placed in corresponding anatomical positions using rotation and displacement tools. The position of the eyes was determined by the eye sockets in the polygonal mesh model of the fetal skull. The HU values of maternal uterus, placenta, amniotic fluid, fetal brain, fetal soft tissue, fetal liver, fetal bone cortex, and fetal bone marrow were measured using the Image J software[1] and transferred to corresponding tissue density using the formula given by Schneider et al.[22] The organs position was carefully adjusted to avoid overlaps and to ensure the organs are located inside the chest and abdominal cavity.

The personalized computational models of the two pairs of twin fetuses at gestational ages of 22 and 30 weeks were constructed with 25 identified organs/tissues. The NURBS-based pregnant patient phantoms and fetus models were voxelized using an in-house C++ code for further Monte Carlo-based radiation transport simulations. The elemental composition of tissues/organs was according to the ICRP publication 89.[23] The maternal abdominal circumference, fetal skin/skull depth, fetal femoral length, humeral length, head circumference, and biparietal diameter were measured and given in Table 1. The fetal skin and fetal skull depth refer to the shortest distance from the foremost skin or skull center of the fetus to the anterior surface of the maternal outline, respectively. The abdominal circumference of the pregnant woman is determined by the perimeter of the belly button of the pregnant woman.

Figure 2 shows the abdominal models of two pregnant women with twins constructed in this study. In the 22-weeks phantom, the relative positions of the twin fetuses were upper position and lower position

[1] https://imagej.nih.gov/ij/

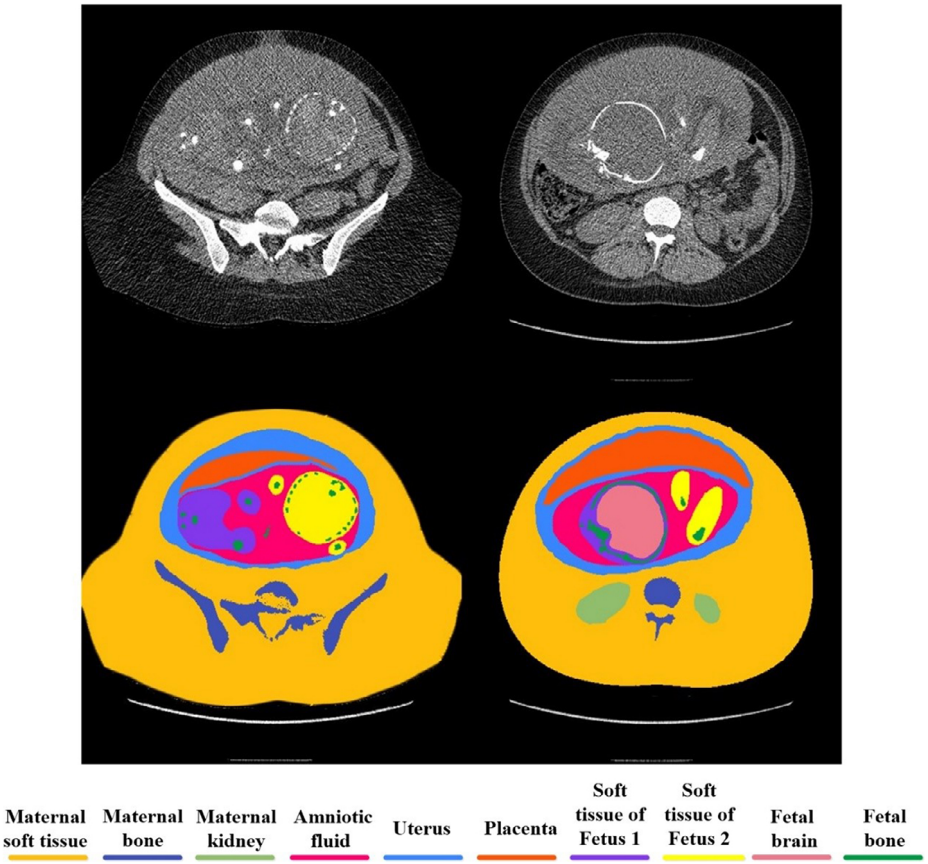

FIGURE 1 CT images of multiple pregnancy patients and their segmentations. (a) Pregnant patient at 22-weeks gestational age and (b) at 30-weeks gestational age (the contours of twin fetuses are represented with different colors).

while in the 30-weeks phantom, the relative positions of the twin fetuses were left position and right position, respectively. The four developed models of twin fetuses are named as $Fetus_{up}$, $Fetus_{down}$, $Fetus_{left}$, and $Fetus_{right}$, respectively, according to their relative positions. Figure 3 shows the individual models for each twin fetuses where the light blue tissue refers to the uterus, while the fetal skull is translucent to illustrate the fetal brain. The placenta (rose pink) is only shown in the right view of Figure 2.

2.2 | CT scanner models

This study included three constructed CT scanner models, namely the GE Discovery CT 750 HD scanner, Siemens SOMATOM Definition Edge scanner, and United Imaging Healthcare uCT 760 128-slice CT scanner. The models of the GE Discovery CT 750 HD scanner, Siemens SOMATOM Definition Edge scanner, and United Imaging Healthcare uCT 760 128-slice CT scanner have been validated in previous studies,[15,24–26] showing good agreement between MC simulations and experimental measurements with no statistically significant differences between estimated organ doses obtained from TLD measurements and MC simulations. The source of each CT system was realistically modeled using x-ray energy spectrums generated using SpekCalc[27] with the associated inherent filtration and half value layer (HVL) extracted from user's manuals. The model of bowtie filter and beam collimators for each scanner were carefully constructed based on information provided by manufacturers. The geometry of each CT gantry, including the source to detector distance, focal spot size, fan angle, etc., were taken into account in the simulation of corresponding CT scanners. The scan length for the investigated two cases were 51.5 and 49.5 cm, respectively.

2.3 | Monte Carlo simulations

The three CT scanner models and the developed computational phantoms of pregnant patients with twins were integrated in the MCNPX code.[28] The scan length of the simulated CT was consistent with the actual examination of pregnant patients, covering the abdomen and pelvis region. The simulation of CT examinations was performed with a helical source path for the GE Discovery CT 750 HD and Siemens SOMATOM Definition Edge scanners while radiation dose calculations were performed using 16 sources along the scan trajectory[8]

TABLE 1 Measurement of anatomical parameters of pregnant patients and twin fetuses.

Gestational age (weeks)	Maternal_Abdominal circumference (cm)	Femur length (mm)	Humerus length (mm)	Biparietal diameter (mm)	Head circumference (mm)	Fetus_Abdominal circumference (mm)	Fetal skull depth (mm)	Fetal depth (mm)	Scan length (cm)	Note
22	100.9	27.88	26.01	43	153.9	168.7	89.34	60.01	51.5	$Fetus_{down}$
		31.41	30.17	48.99	163.7	184.6	65.8	51.59	51.5	$Fetus_{up}$
30	108.5	57.67	51.9	76.67	272.2	234.6	113.6	63.67	49.5	$Fetus_{left}$
		57.66	54.75	87.91	291.8	230.8	133	52.3	49.5	$Fetus_{right}$

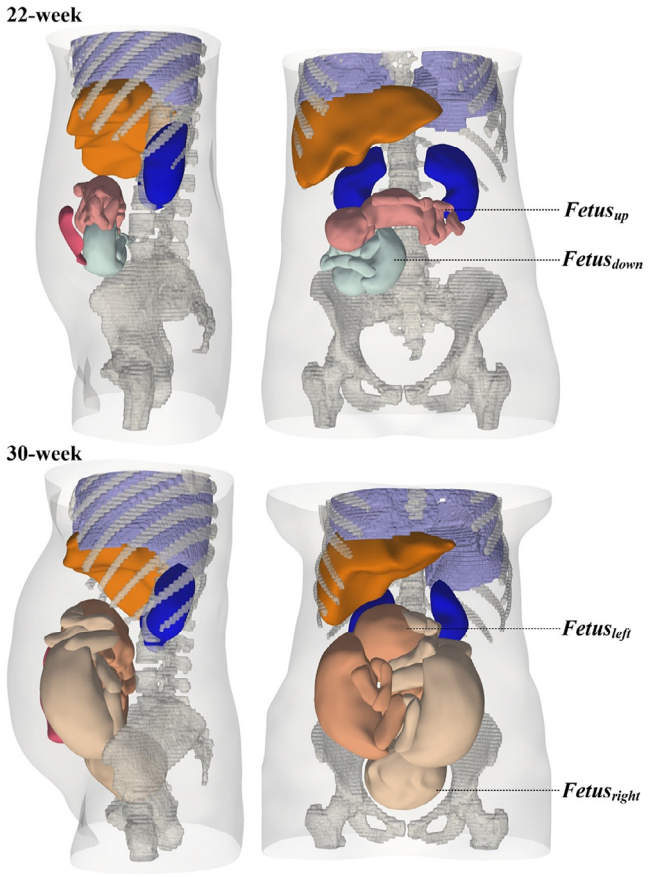

FIGURE 2 Visualization of personalized phantoms of multiple pregnancy patients.

for the United Imaging Healthcare uCT 760 128-slice CT scanner. For helical CT scans on the developed patient model, each simulation was repeated six times with the tube starting angle differing by 60° because of the unknown tube-starting angles in the actual examinations. The energy deposition in the 25 fetal organs and maternal body was recorded and used for radiation dosimetry calculations. The energy deposition in 25 fetal organs was recorded. Finally, the estimated dosimetry results were normalized to the CT dose index ($CTDI_{vol}$) of each scanner protocol.

2.4 | Calculation of fetal absorbed doses

To calibrate the developed CT scanner models and convert the simulated relative dose tallies to absolute absorbed dose values, a series of free-in-air dose measurements were performed using 10 cm pencil chambers on CT scanners where the ion chamber was positioned at the isocenter with the long axis aligned with the axis of gantry rotation. Free-in-air measurements were performed in single axial scans while Monte Carlo simulations were performed for the detector in air under the same examination conditions. The absorbed dose

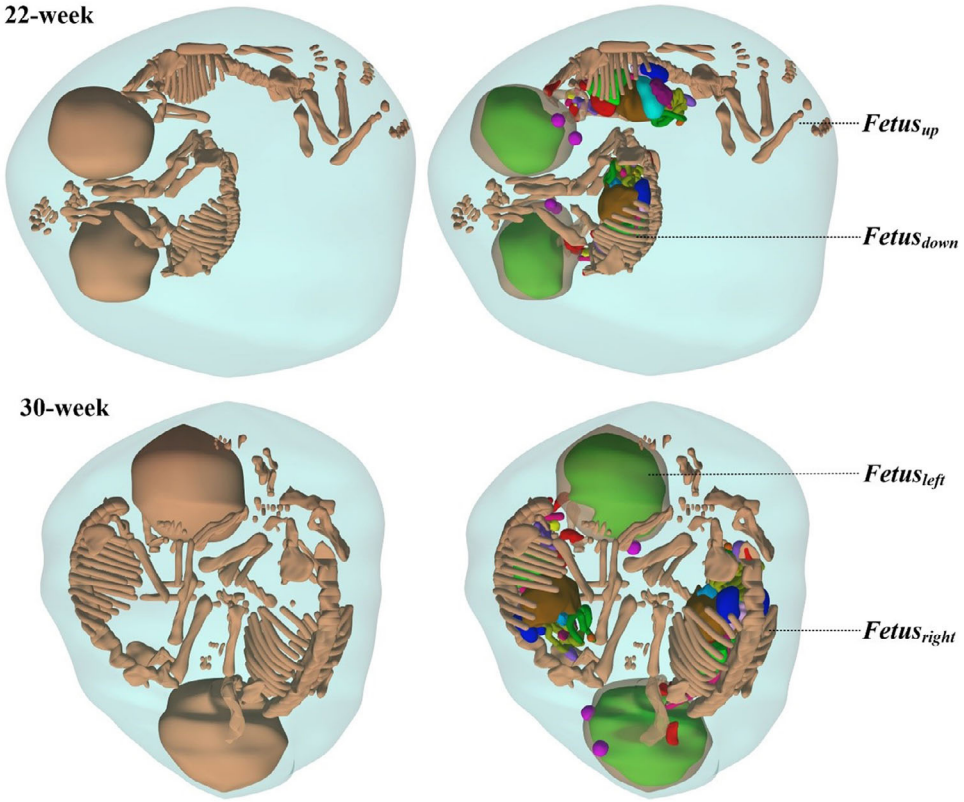

FIGURE 3 Visualization of the constructed models of twin fetuses.

derived from simulations can then be calculated as[25]:

$$D_{\text{estimated}} = d_{\text{simulated}} \times \text{mAs} \times \text{CF}$$

where $\boldsymbol{d}_{\text{simulated}}$ is the absorbed dose per photon emitted from the source obtained in simulations; mAs is the effective tube current–time product value; and CF is a calibration factor[29] to scale the simulation results.[25] The scanner-dependent absolute fetal dose is given in mGy while the normalized-organ dose coefficient can be obtained by dividing the absolute fetal dose by CTDI_{vol}, which proved to be effectively independent from scanner type.[30]

3 | RESULTS

3.1 | Evaluation of developed phantoms for pregnant patients with twins

Table 1 lists the measured anatomical parameters of the maternal body as well as the two pairs of twin fetuses. The abdominal circumference of the two pregnant models were 100.9 and 108.5 cm, respectively. For the *Fetus*$_{up}$ and *Fetus*$_{down}$ of the 22-weeks pregnancy phantom, the fetal skin depths are 60.01 and 51.59 mm; fetal skull depths are 89.34 and 65.80 mm; fetal abdominal circumferences are 168.70 and 184.60 mm; femur length are 27.88 and 31.41 mm; humerus length are 26.01 and 30.17 mm; biparietal diameter are 43.00 and 48.99 mm; head circumferences are 153.9 and 163.7 mm, respectively. For the *Fetus*$_{left}$ and *Fetus*$_{right}$ of the 30-weeks pregnancy phantom, the fetal skin depths are 63.67 and 52.3 mm; fetal skull depths are 113.6 and 133 mm; fetal abdominal circumferences are 234.6 and 230.8 mm; femur length are 57.67 and 57.66 mm; humerus length are 51.9 and 54.75 mm; biparietal diameter are 76.67 and 87.91 mm; and head circumference are 272.2 and 291.8 mm, respectively. Table 2 lists the masses of 25 fetal organs where the mean absolute organ mass differences between the two twins are 17.8% and 9.3% for the 22-weeks phantom and 30-weeks phantom, respectively.

3.2 | Fetal radiation dose

The fetal organ doses from the simulated CT scanner models of GE, Siemens, and United Imaging Healthcare were estimated. Figure 4 shows the estimated fetal doses for the whole body, bone, brain and liver. For the total body, the absorbed dose from the GE Discovery CT 750 HD scanner is about 61.93% and 31.46% higher than that of Siemens SOMATOM Definition Edge scanner and United Imaging Healthcare uCT 760 128-slice CT scanner, respectively. For all investigated fetal organs,

TABLE 2 Organ masses for computational phantoms for twin fetuses.

Organ/tissue	22-weeks			30-weeks		
	$Fetus_{down}$	$Fetus_{up}$	Diff	$Fetus_{left}$	$Fetus_{right}$	Diff
Fetal soft-tissue	117.81	133.13	11.51%	684.82	739.14	7.35%
Fetal skeleton	61.81	71.09	13.05%	265.15	277.90	4.59%
Fetus bone marrow	3.94	4.71	16.35%	18.62	20.77	10.35%
Fetus brain	29.94	40.45	25.98%	201.35	243.10	17.17%
Fetus esophagus	0.21	0.26	19.23%	1.02	1.11	8.11%
Fetus eyes	0.61	0.60	−1.67%	2.93	3.17	7.57%
Fetus thyroid	0.10	0.17	41.18%	0.59	0.62	4.84%
Fetus spinal cord	0.96	0.93	−3.23%	3.04	2.97	−2.36%
Fetus lungs	7.33	8.88	17.45%	32.45	34.98	7.23%
Fetus heart	1.58	1.82	13.19%	7.79	8.50	8.35%
Fetus kidneys	2.14	2.46	13.01%	10.40	11.24	7.47%
Fetus liver	10.12	11.62	12.91%	51.89	56.88	8.77%
Fetus stomach	2.14	2.29	6.55%	9.42	10.79	12.70%
Fetus gall bladder	0.33	0.38	13.16%	1.62	1.79	9.50%
Fetus slivary grand	0.54	0.64	15.63%	2.75	3.08	10.71%
Fetus LI	0.89	0.99	10.10%	3.96	4.17	5.04%
Fetus SI	1.89	2.33	18.88%	9.15	10.84	15.59%
Fetus UB	0.40	0.40	0.00%	1.94	2.15	9.77%
Fetus skin	19.61	21.54	8.96%	71.80	81.52	11.92%
Fetus ovaries	0.05	0.03	−66.67%	0.16	0.14	−14.29%
Fetus testis	0.06	0.09	33.33%	0.32	0.40	20.00%
Fetus adrenal	0.58	0.60	3.33%	2.49	2.74	9.12%
Fetus pancreas	1.34	1.50	10.67%	3.53	3.55	0.56%
Fetus spleen	0.18	0.22	18.18%	1.82	1.99	8.54%
Fetus thymus	0.77	0.87	11.49%	4.47	4.96	9.88%

Note: The organ mass is given in gram.

the GE Discovery CT 750 HD scanner resulted in the highest absorbed dose while the radiation dose from Siemens SOMATOM Definition Edge scanner model was the lowest.

After normalizing the radiation dose with $CTDI_{vol}$, Table 3 lists the averaged absorbed doses for three scanners for 25 fetal organs of the two pairs of twin fetuses. The mean fetal organ dose of the 22-weeks model is 13.90% higher than that of the 30-weeks pregnancy model. For all fetuses, the absorbed dose in the fetal skeleton and bone marrow are significantly higher than that of other organs due to the greater tissue density of the skeleton and bone marrow as well as the absorption of scattered radiation. For the 22-weeks and 30-weeks pregnancy models, the fetal doses to the skeleton are about 4.1 times and 3.4 times higher than that of soft tissue.

For the 22-weeks pregnancy model, the total body doses of $Fetus_{down}$ and $Fetus_{up}$ were 2.26 and 2.03 mGy while for the 30-weeks model, the absorbed doses to $Fetus_{left}$ and $Fetus_{right}$ were 1.68 and 1.56 mGy, respectively. Figure 5 compares the normalized fetal dose of twin fetuses with results reported in the literature,[9,13,31–33] where the data of Xie et al.[15] and Angel et al.[16] were calculated according to formulas reported in these references. Thirty pregnant patients were involved in Xie's study, where the average gestation age, conceptus depth, maternal perimeter, and water equivalent diameter were 18.4 weeks, 17.07, 107.7, and 28.8 cm, respectively. Twenty-four pregnant patients were involved in Angel's study, where the average gestational age, maternal perimeter, and fetal depth were 19.7 weeks, 101.0, 107.7, and 6.1 cm, respectively. For fetus at 22-weeks gestational age, the reported fetal dose ranges between 4.69 and 12.39 mGy/100 mAs while the normalized absorbed dose for $Fetus_{down}$ and $Fetus_{up}$ are 8.86 and 9.88 mGy/100 mAs, respectively. For fetus at 30-weeks gestational age, the reported fetal dose ranges between 4.69 and 11.48 mGy/100 mAs while the normalized absorbed doses for $Fetus_{left}$ and $Fetus_{right}$ are 7.36 and 6.81 mGy/100 mAs, respectively. The estimated fetal doses from the dosimetry schema

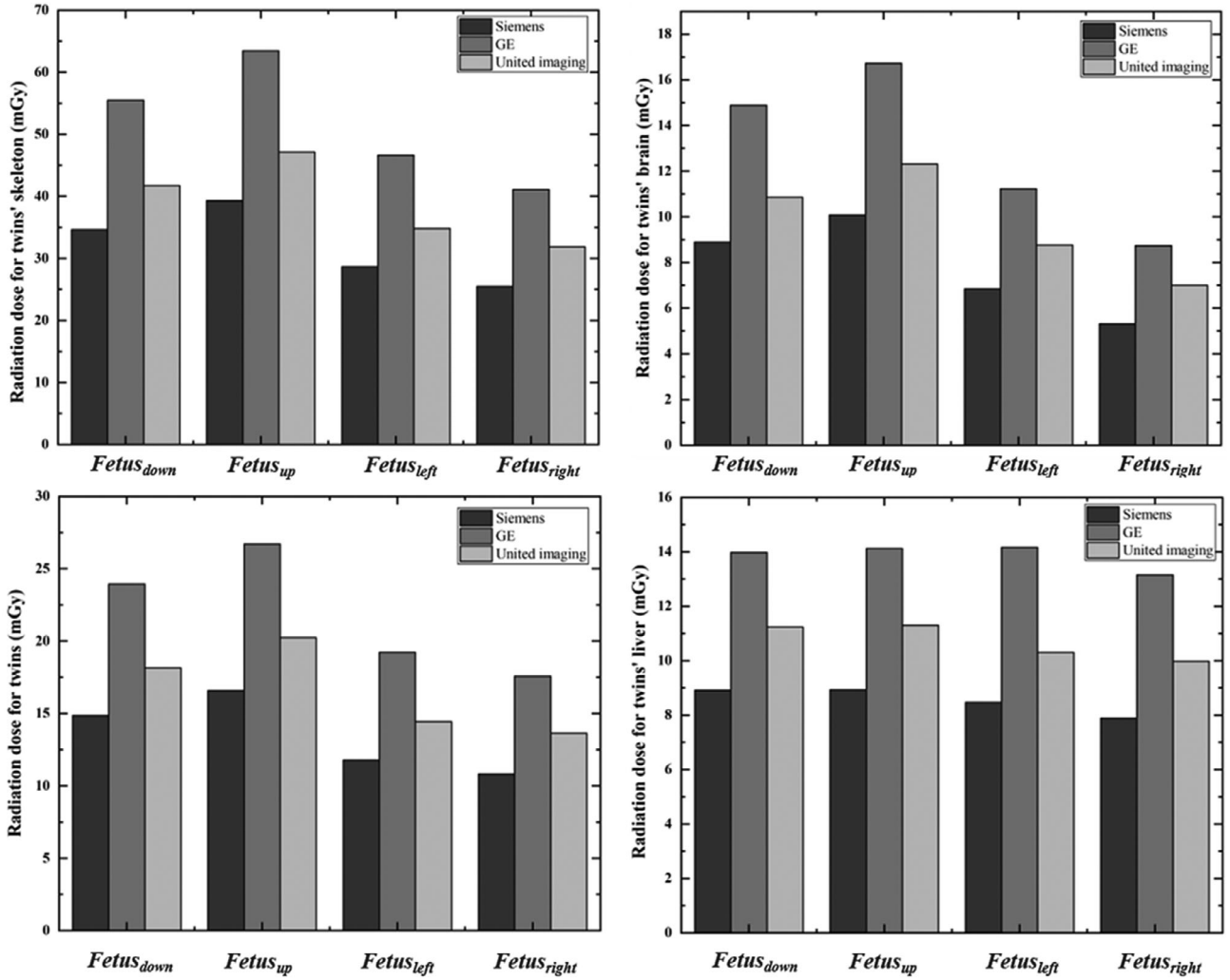

FIGURE 4 Comparison of fetal radiation doses among three CT scanners.

adopted by Angel et al.[16] and Xie et al.[15] are 35.95% and 62.04% higher than the average fetal dose of twin fetuses at 30-weeks gestational age.

3.3 | Absorbed dose differences between twin fetuses

Figure 6 compares the $CTDI_{vol}$-normalized organ dose for twin fetuses at the same gestational age. Table 4 lists the calculated percentage radiation dose differences between two fetuses of twins. For 22-weeks and 30-weeks pregnancy models, the mean absolute differences of organ dose between twin fetuses are 11.4% and 13.7%, respectively. For 22-weeks pregnancy model, the fetal eyes present the highest organ dose difference (39.64%) while the fetal testis presents the highest organ dose difference for the 30-weeks model.

Table 5 summarizes the percentage differences of total body absorbed doses between twin fetuses. Xie et al.[15] and Angel et al.[16] reported the following formulas to calculate fetus dose:

$$D_{fetus} = 2.265 - 0.01 \times \mathrm{FD} - 0.00869 \times \mathrm{MAC}$$

$$D_{fetus} = 24.56 - 0.029 \times \mathrm{FD} - 0.119 \times \mathrm{MAC}$$

where FD is fetal depth, and MAC is maternal abdominal circumference. The calculated dose difference between twin fetuses according to these formulas in our twin fetus case is less than 1%. However, the personalized radiation dosimetry based on patient-specific phantoms and Monte Carlo calculation adopted in this study showed that the dose differences of fetal body between twin fetuses were 11.55% and 7.51% for the 22-weeks and 30-weeks pregnant patients, respectively.

4 | DISCUSSION

This work investigated the radiation dosimetry characteristics of twin fetuses for pregnant patients undergoing

TABLE 3 Calculated organ doses (mGy/100 mAs) with standard deviation for twin fetuses from abdominal CT examinations.

Organ/tissue	22-weeks		30-weeks	
	Fetus down	*Fetus up*	*Fetus left*	*Fetus right*
Fetal soft tissue	0.66 ± 0.01	0.72 ± 0.01	0.63 ± 0.01	0.65 ± 0.01
Fetal skeleton	2.63 ± 0.13	2.99 ± 0.07	2.29 ± 0.03	2.05 ± 0.03
Fetus bone marrow	1.33 ± 0.03	1.64 ± 0.02	1.05 ± 0.01	0.96 ± 0.02
Fetus brain	0.69 ± 0.03	0.78 ± 0.05	0.56 ± 0.01	0.44 ± 0.03
Fetus esophagus	0.58 ± 0.03	0.64 ± 0.03	0.59 ± 0.02	0.52 ± 0.02
Fetus eyes	0.54 ± 0.05	0.76 ± 0.06	0.44 ± 0.02	0.48 ± 0.03
Fetus thyroid	0.68 ± 0.02	0.76 ± 0.03	0.68 ± 0.01	0.55 ± 0.02
Fetus spinal cord	0.65 ± 0.02	0.69 ± 0.01	0.64 ± 0.01	0.67 ± 0.01
Fetus lungs	0.63 ± 0.02	0.69 ± 0.03	0.64 ± 0.01	0.61 ± 0.03
Fetus heart	0.62 ± 0.04	0.70 ± 0.03	0.60 ± 0.01	0.57 ± 0.02
Fetus kidneys	0.70 ± 0.03	0.73 ± 0.02	0.66 ± 0.01	0.78 ± 0.02
Fetus liver	0.68 ± 0.04	0.69 ± 0.03	0.68 ± 0.01	0.64 ± 0.03
Fetus stomach	0.61 ± 0.05	0.73 ± 0.06	0.58 ± 0.02	0.66 ± 0.05
Fetus gall bladder	0.66 ± 0.05	0.60 ± 0.03	0.63 ± 0.01	0.62 ± 0.04
Fetus slivary grand	0.56 ± 0.03	0.63 ± 0.03	0.53 ± 0.01	0.48 ± 0.02
Fetus LI	0.65 ± 0.03	0.69 ± 0.02	0.58 ± 0.01	0.68 ± 0.02
Fetus SI	0.66 ± 0.06	0.69 ± 0.05	0.59 ± 0.02	0.71 ± 0.04
Fetus UB	0.69 ± 0.01	0.74 ± 0.01	0.63 ± 0.00	0.80 ± 0.01
Fetus skin	0.71 ± 0.02	0.78 ± 0.04	0.67 ± 0.04	0.64 ± 0.04
Fetus ovaries	0.62 ± 0.06	0.66 ± 0.07	0.55 ± 0.03	0.67 ± 0.05
Fetus testis	0.60 ± 0.02	0.66 ± 0.02	0.53 ± 0.01	0.69 ± 0.04
Fetus adrenal	0.59 ± 0.02	0.64 ± 0.02	0.60 ± 0.01	0.65 ± 0.04
Fetus pancreas	0.66 ± 0.04	0.68 ± 0.04	0.59 ± 0.02	0.69 ± 0.05
Fetus spleen	0.62 ± 0.06	0.80 ± 0.04	0.56 ± 0.01	0.72 ± 0.04
Fetus thymus	0.58 ± 0.01	0.60 ± 0.01	0.58 ± 0.01	0.49 ± 0.01

diagnostic CT examinations. Two patient-specific computational phantoms at the second and third trimesters were constructed based on CT images of pregnant females. Models of twin fetuses at 22-weeks and 30-weeks gestational age were developed and used for organ-level radiation dosimetry through combination with validated CT scanner models for Monte-Carlo simulations. The dosimetric calculation showed that the fetal skeleton and bone marrow received the highest absorbed dose in pelvic and abdomen CT scans while the absorbed dose to other fetal organs were close to each other. Special attention should be paid for radiation risks to the fetal skeleton when performing CT examinations on pregnant patients.

The birth rate of twins has soared thanks to the progress in healthcare, the maturity of assisted reproductive technology, popularity of novel fertility treatment methods, and prolongation of childbearing age.[18] However, the dosimetry aspects of multiple pregnancy may differ significantly from singleton owing to the discrepancies in anatomical characteristics and location and size of conceptuses. Although simplified fetal dosimetry schemes have been used in clinical practice,[15,16] radiation dosimetry for twin fetuses from CT imaging procedures have not been sufficiently addressed. This study aimed to estimate the radiation dose to twin fetuses during pelvic/abdominal CT examinations for pregnant patients and compared the radiation dose difference between twin fetuses. The construction of patient-specific models for twin fetuses should improve the accuracy of radiation dose estimation. Based on published fetal radiation dosimetry schema,[15,16] the estimated absorbed dose difference between twin fetuses is less than 1%. However, our results demonstrated that for the investigated multiple pregnancy patients, the absolute organ dose differences between twin fetuses ranges between 0.63% and 39.64% with an average value of 12.85% while the mean absorbed dose difference for fetal body is 9.53%. The twin models used in this study were created from clinical CT images, and as such they reflect more accurately the human anatomy compared to simplified models, which renders the dose calculation more reliable. The absorbed dose differences between twin fetuses can be attributed

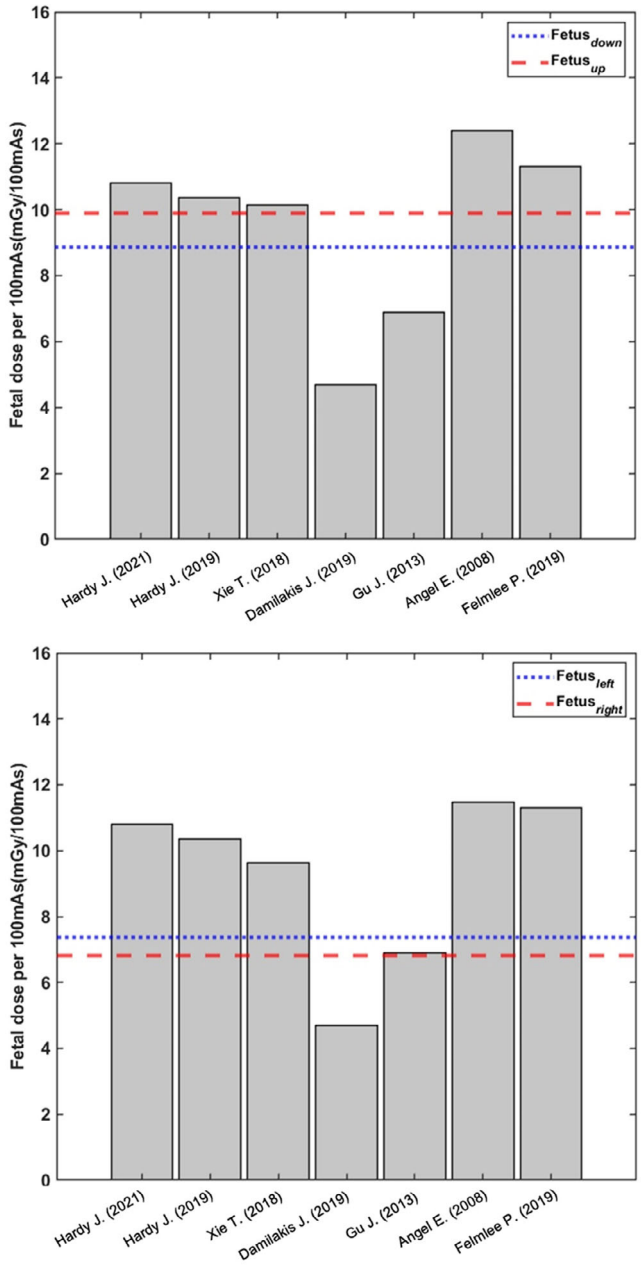

FIGURE 5 Comparison of radiation doses for fetal body between this study and results reported in the literature.[9,13,15,16,31–33]

TABLE 4 Differences of organ doses between twin fetuses.

Organ/tissue	Organ dose differences	
	22-weeks	30-weeks
Fetal soft tissue	9.01%	3.18%
Fetal skeleton	13.62%	−10.52%
Fetus bone marrow	23.67%	−8.76%
Fetus brain	12.98%	−21.50%
Fetus esophagus	10.96%	−12.54%
Fetus eyes	39.64%	11.20%
Fetus thyroid	11.80%	−19.02%
Fetus spinal cord	5.72%	4.36%
Fetus lungs	9.86%	−5.20%
Fetus heart	11.68%	−6.27%
Fetus kidneys	4.99%	18.35%
Fetus liver	0.63%	−5.79%
Fetus stomach	18.29%	12.78%
Fetus gall bladder	−9.99%	−1.67%
Fetus slivary grand	14.24%	−9.92%
Fetus LI	6.08%	16.93%
Fetus SI	4.54%	19.59%
Fetus UB	7.19%	27.69%
Fetus skin	9.16%	−4.28%
Fetus ovaries	5.34%	21.01%
Fetus testis	8.85%	31.12%
Fetus adrenal	8.55%	8.82%
Fetus pancreas	3.96%	17.68%
Fetus spleen	29.83%	29.40%
Fetus thymus	4.10%	−15.76%

TABLE 5 Absorbed dose differences for the total body between twin fetuses.

Twins dose difference	This work	Xie et al.[15]	Angel et al.[16]
22-week	11.55%	0.63%	0.20%
30-week	7.51%	0.90%	0.29%

to the variability in source-fetus distance and fetal organ masses. The dosimetry schema based on singleton pregnancy overestimated the mean absorbed dose for twin fetuses and underestimated the radiation dose differences between twin fetuses. These dosimetric models are based on results calculated using standard fetal phantoms. The differences observed may be attributed to factors such as fetal gestational age and CT modeling. Our study highlights the importance of the twin fetal model in specific contexts, particularly for pregnant women with twin pregnancies. This is especially relevant for clinical decision-making and the potential individual differences that may arise in research. For multiple pregnancy patients, the calculated fetal radiation dose from a single CT examination is far below the threshold of deterministic effect. However, when multiple CT scans are required for diagnostic purposes, accurate estimation of fetal radiation dose and optimization of scanning protocols could be recommended.

This work inherently bears a number of limitations. First of all, only two pregnant patients with twins were enrolled in this study, reflecting a small sample size and a small number of phantoms. Additional radiation dosimetry studies on multiple pregnancy patients are desired to confirm the findings of this work. In addition, this study only evaluates and reports the doses for two pregnant women with twin pregnancies, without

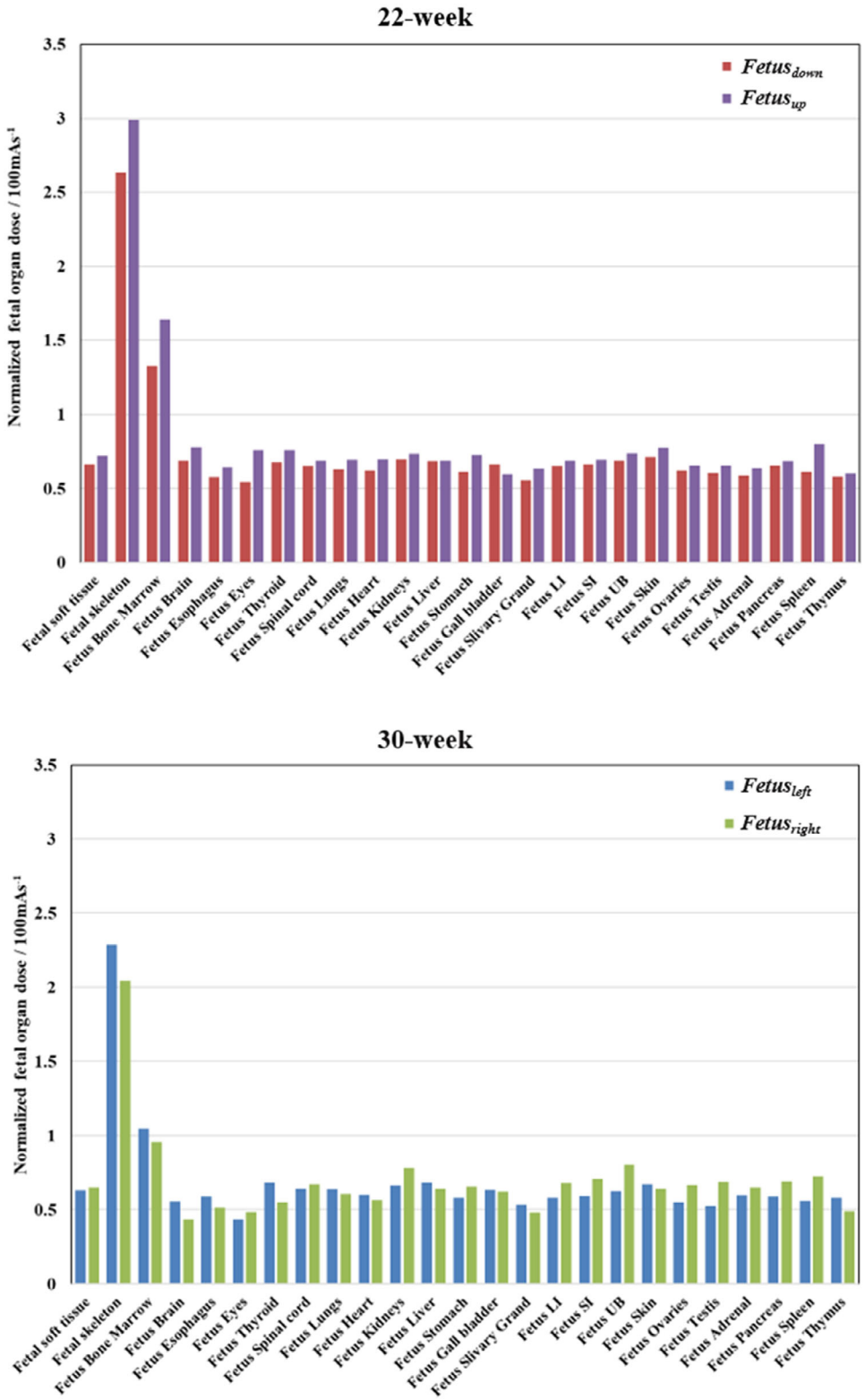

FIGURE 6 Normalized organ doses for twin fetuses. (Due to visibility constraints, the uncertainty is not plotted in the figure. The uncertainties are presented in Table 3.)

comparing the dose differences between twin pregnancies and single-fetus standard models. In the future works, we will calculate and assess the impact of smaller fetal body size and deviations in fetal position from the center on dose estimates in multiple pregnancies. Furthermore, we will investigate and quantify the various sources of uncertainty in the dose calculations to enhance the accuracy and reliability of our findings. By enhancing both the quantity and the quality of clinic data, future studies will offer more accurate and clinically relevant insights into dose calculations for twin fetuses.

5 | CONCLUSION

Radiation dosimetry to the fetus is essential for risk-benefit assessment and CT scanning protocol optimization for pregnant patients undergoing radiological examinations. The variability in body weight and organ masses affects the absorbed doses to twin fetuses. Singleton-based fetal radiation dosimetry formula is not applicable for radiation dose estimation of fetuses in multiple pregnancy patients. Hence, the construction of comprehensive personalized fetal radiation dosimetry schema is highly desired. The personalized NURBS-based fetal models developed in this study provide more accurate fetal radiation dosimetry estimates for patients pregnant with twins and have an inherent advantage of deformation and displacement. These models could be used to construct a more representative model for twin fetuses at different gestational ages. The developed computational phantoms for multiple pregnancy patients will be included in a virtual patient library. This work also fills a gap in radiation dosimetry estimates for multiple pregnancy patients and contributes to a better understanding of model-induced uncertainties in external radiation dosimetry for the developing fetus.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets used in the current study are available from the corresponding author on reasonable request.

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