Radiation Dose to the Fetus for Pregnant Patients Undergoing Multidetector CT Imaging: Monte Carlo Simulations Estimating Fetal Dose for a Range of Gestational Age and Patient Size¹

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Purpose:

To use Monte Carlo simulations of a current-technology multidetector computed tomographic (CT) scanner to investigate fetal radiation dose resulting from an abdominal and pelvic examination for a range of actual patient anatomies that include variation in gestational age and maternal size.

Materials and Methods:

Institutional review board approval was obtained for this HIPAA-compliant retrospective study. Twenty-four models of maternal and fetal anatomy were created from image data from pregnant patients who had previously undergone clinically indicated CT examination. Gestational age ranged from less than 5 weeks to 36 weeks. Simulated helical scans of the abdominal and pelvic region were performed, and a normalized dose (in milligrays per 100 mAs) was calculated for each fetus. Stepwise multiple linear regression was performed to analyze the correlation of dose with gestational age and anatomic measurements of maternal size and fetal location. Results were compared with several existing fetal dose estimation methods.

Results:

Normalized fetal dose estimates from the Monte Carlo simulations ranged from 7.3 to 14.3 mGy/100 mAs, with an average of 10.8 mGy/100 mAs. Previous methods yielded values of 10–14 mGy/100 mAs. The correlation between gestational age and fetal dose was not significant ($P = .543$). Normalized fetal dose decreased linearly with increasing patient perimeter ($R^2 = 0.681$, $P < .001$), and a two-factor model with patient perimeter and fetal depth demonstrated a strong correlation with fetal dose ($R^2 = 0.799$, $P < .002$).

Conclusion:

A method for the estimation of fetal dose from models of actual patient anatomy that represented a range of gestational age and patient size was developed. Fetal dose correlated with maternal perimeter and varied more than previously recognized. This correlation improves when maternal size and fetal depth are combined.

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Diagnostic computed tomographic (CT) imaging is sometimes necessary in a pregnant patient. When a radiologist needs to decide if the diagnostic benefits will outweigh the risks of radiation, it is important to have a reasonably accurate estimate of the radiation dose that the conceptus (fetus or embryo) will receive. Furthermore, in cases in which pregnancy is discovered during or after CT examination, the patient and/or physician may request an estimate of the radiation dose received by the conceptus. For the remainder of this article, the term *fetus* will be used to refer to either an embryo or a fetus and will therefore be used to describe a conceptus at any gestational age.

It is not known definitively how much radiation dose a fetus receives during CT examination, because this cannot be measured directly. Some methods to estimate fetal dose exist, but these estimates are limited by their simplifying assumptions. Existing fetal dose estimation methods are based on phantom measurements and/or geometric phantom simulation methods.

The method used to estimate fetal dose developed by Felmlee et al (1) is based on anthropomorphic phantom measurements and measured CT dose index (2). More recently, Hurwitz et al (3) estimated fetal dose by using physical measurements from internal dosimeters in an anthropomorphic phantom that was

modified to represent a newly pregnant patient and a patient who was 3 months pregnant.

Other approaches to estimate fetal dose are based on Monte Carlo simulations of geometric patient models. In these methods, dose to the uterus is used as an estimate of dose to the fetus at an early gestational age. One such method is the ImPACT CTDosimetry dose calculator (CTDosimetry.xls, version 0.99×; ImPACT, London, England) (4), which is based on Monte Carlo simulations performed by the National Radiological Protection Board (5) with the use of a geometric Medical Internal Radiation Dose (MIRD) phantom model (6). Another similar method is the CT-Expo software (version 1.5.1; Medizinische Hochschule, Hannover, Germany) (7,8), which estimates organ dose based on simulations performed by Zankl et al at the German National Research Center with the Eva geometric phantom model to represent a standard-size female patient (9,10).

The MIRD and Eva phantoms consist of geometric shapes representing human organs for a standard-size patient model. Although these geometric phantoms do not represent pregnant patient anatomy, ImPACT CTDosimetry and CT-Expo software can be used to estimate radiation dose to the uterus, which may be used to approximate fetal dose during the first 8 weeks of gestation. A patient-based voxelized model of a patient who is 30 weeks pregnant does exist (11), but, to the best of our knowl-

edge, this model has only been used for the estimation of radiation dose in experiments that involved radiation sources other than CT.

In summary, existing methods for the estimation of fetal dose for pregnant patients undergoing CT examinations assume early term pregnancy in a single-size patient model with an average, non-varying maternal anatomy. These dose estimates do not take into account natural variations, such as fetal presentation and gestational age. Differences in these attributes can cause overestimation or underestimation of up to 100% for fetal dose at radiologic examinations (12).

To overcome these limitations, simulations should model specific scanner and maternal and fetal characteristics. The purpose of this study was to use Monte Carlo simulations with a current-technology multidetector CT scanner to estimate fetal dose at abdominal and pelvic CT examination with models of pregnant patients that represented a range of gestational ages and maternal sizes.

Materials and Methods

Patient Images

Twenty-four voxelized models of maternal and fetal anatomy were created on

Advances in Knowledge

- Radiation dose to the fetus at CT imaging in pregnant patients was estimated with examples of actual pregnant patient anatomy that represented a range of gestational ages.
- Radiation dose to the fetus correlates with patient size as measured by the perimeter around the mother.
- There was no correlation between gestational age and fetal dose ($P = .543$).
- The average fetal doses were estimated to be 10.8 mGy per 100 mAs for a specific scanner model, with a range from 7.3 to 14.3 mGy/100 mAs.

Implications for Patient Care

- 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.
- Fetal dose estimates for a single-pass abdominal and pelvic acquisition are below the consensus levels for negligible risk (50–150 mGy) and well below the actionable level of 150 mGy.
- Modulation of tube current with respect to patient size should be used to decrease fetal dose for smaller maternal sizes.

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Abbreviation:

MIRD = Medical Internal Radiation Dose

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the basis of image data from a cohort of 31 pregnant patients who previously underwent clinically indicated abdominal and pelvic CT examination. The original CT examinations were performed unrelated to this study and were often in emergency and/or trauma patients (such as those who were injured in a motor vehicle accident). Institutional review board approval was obtained for this Health Insurance Portability and Accountability Act-compliant study for the use of the anonymized CT images, as well as for additional anonymized patient data (ie, patient weight and gestational age). The 24 patient models were selected to represent a range of gestational ages; seven cases were excluded because of a lack of sufficient volumetric image data (images did not fully cover the uterus) or because gestational ages were similar to those of other cases already in the cohort. The set of 24 patients included gestational ages ranging from less than 5 weeks to 36 weeks, with an average gestational age of 20 weeks. The cohort included six patients in the first trimester of pregnancy, 10 patients in the second trimester, and eight patients in the third trimester. Examples of these CT images are shown in Figure 1. The 24 models created as part of this study are publicly available at <http://medqia.org/~mcnitt/FetalModels>.

The original image data were acquired between January 2002 and February 2006 with 120-kVp acquisition protocols, with image thickness varying from 1.25 to 10

mm. The patients in the cohort were originally scanned with one of the following scanners: HighSpeed CT/I, LightSpeed QX/i, LightSpeed Ultra, LightSpeed PRO, LightSpeed 16, or LightSpeed VCT (GE Healthcare, Waukesha, Wis). Oral contrast agent had been used in 13 of the 24 CT examinations. The cranial-caudal length of each voxelized patient model was dependent on the length of CT image data available. The average length of image data was 46.2 cm, and all of the image series included, at a minimum, the patient anatomy from the lower thorax to the pubic symphysis.

Two anatomic measures were obtained from each patient's images by one of the authors (E.A.), who had been trained in reviewing CT image data. These measures were used to assess the size of the mother and the location of the fetus within the mother. The patient size metric was the outer (skin) perimeter of the patient on the image containing the three-dimensional geometric centroid of the fetus. The perimeter was determined by using a semiautomated threshold-based contouring technique. Fetal depth was measured manually as the distance from the anterior skin surface to the most anterior part of the fetus. The patient perimeter and fetal depth measures are illustrated in Figure 2.

Patient Models

To estimate fetal dose, three regions of interest were identified for each set of

patient data by one of two board-certified radiologists (C.V.W., N.Y.). The radiologist contoured the uterus, gestational sac (when visible), and fetus (when visible), which resulted in a set of voxels that were labeled as belonging to these three tissue groups. Images were subsampled from a 512×512 matrix to a 128×128 matrix to reduce simulation time.

Voxels within the fetus were modeled as soft tissue or soft bone, depending on the CT number (in Hounsfield units). The voxels in the gestational sac were modeled as water, and the voxels in the uterus were modeled as soft tissue. Each voxel of the mother outside these fetal regions was modeled as one of six tissue types (lung, fat, water, muscle, bone, or air) (13). The process of creating voxelized models from the original patient images is illustrated in Figure 3.

Multidetector CT Source Model

A previously validated multidetector CT source model was created by using Monte Carlo simulation-based techniques (14–18). The CT scanner modeled was a LightSpeed 16 (GE Medical Systems). The scanner's x-ray spectrum, filtration, and geometry were obtained from the manufacturer and confirmed through measurements. The x-ray spectrum was initially described as a function of the number of photons at 1-keV energy intervals, which was then converted to a cumulative distribution func-

Figure 1

Figure 1: CT images in three patients in the cohort at gestational age of 7 weeks (left), 24 weeks (middle), and 36 weeks (right) that demonstrate early term, mid-term, and late-term pregnancy, respectively.

Figure 2

Figure 2: CT image with semiautomated contour (dashed line) around the perimeter of the mother on central image in a 35-week-old fetus, as well as the assessment of fetal depth (distance from skin to fetus [double arrow]).

tion for implementation within the Monte Carlo source model (14–18). The multidetector CT model included the bowtie filter and beam collimation. The multidetector CT model was designed to simulate acquisition parameters selected by the user, including beam energy (kilovoltage peak), source path (ie, helical or axial), pitch, total nominal beam collimation, and scan length.

Monte Carlo Simulation of Abdominal and Pelvic CT Examination

The simulated CT examination covered the abdominal and pelvic region. The total length of the simulated examination (including image data and z-axis overscan) was equivalent to the length of the original patient image data. The simulated abdominal and pelvic examination had a beam energy and filtration combination of 120 kVp and body bow tie filter,

which resulted in a first half-value layer at isocenter of approximately 7.8 mm aluminum. The simulated scan had a helical source path with a pitch of 1.0 and had 16 detector rows of 1.25 mm (resulting in 16×1.25 -mm total nominal collimation). Although the actual scanner modeled does not allow these particular acquisition parameters (pitch of 1.0 is not available), the simulation parameters represent a typical abdominal and pelvic examination, and the results can be scaled to any other pitch value. Simulated examinations were performed in all 24 voxelized phantoms. No tube current–time product value was specified; all doses were tallied and reported on a normalized basis of milligrays per 100 mAs.

The simulation involves modeling the x-ray photon transport through the voxelized patients and tallying dose in the voxels that were labeled as uterus,

Figure 3

Figure 3: CT images and voxelized models created from patient images of an early pregnancy (7 weeks) and a later pregnancy (35 weeks). Pink represents the uterus, yellow represents the gestational sac, and red represents the fetus (when visible). In the voxelized model, fetal bone is white, and tissues outside the radiologist's contours range from blue to green.

gestational sac, and fetus. All simulations used the Monte Carlo N-Particle eXtended code (version 2.5.0; Radiation Safety Information Computational Center, Oak Ridge, Tenn) created at the Los Alamos National Laboratory (19,20). Each Monte Carlo simulation was performed with 1–10 million simulated x-ray photons, which were enough to ensure less than 1% statistical error within the tally region of interest (approximately 2 hours run time on an average desktop computer).

Dose Calculations

The average radiation dose to the fetus was tallied when the fetus was distinguishable from the gestational sac and uterus. If the fetus was not visible, the average dose was tallied in the gestational sac. In one voxelized model, with a gestational age less than 5 weeks, the gestational sac was not visible; in this case, the dose was tallied in the uterus. The average dose was computed by averaging the values of dose absorbed in the voxels within the tally region. Absorbed dose within a voxel was computed from the collision kerma, calculated from the Monte Carlo N-Particle eXtended track-length estimate of energy fluence, and multiplied by the material-specific and energy-dependent mass-energy absorption coefficient. The mass-energy absorption coefficients were taken from the tables of Hubbell and Seltzer (21). All reported dose results were normalized per 100 mAs.

Statistical Analysis

The fetal dose estimates from the cohort of voxelized patient models were tested for correlation with each of three independent measures described above: gestational age, perimeter of the mother, and fetal depth. Stepwise multiple linear regression analysis was performed to assess the partial correlation of each variable, and *P* values were calculated to determine statistical significance. A *P* value less than .05 indicated a significant difference.

Existing Methods

There is no reference standard for fetal dose that can be used as comparison for

Table 1

Patient Model Measurements and Radiation Dose per 100 mAs to Fetus according to Gestational Age of 24 Voxelized Models

Gestational Age (wk)	Maternal Perimeter (cm)	Fetal Depth (cm)	Normalized Fetal Dose (mGy/100 mAs)
<5.0	123	10.6	7.3*
5.0	89	4.2	11.8 [†]
5.0	88	7.6	10.3 [†]
6.6	102	10.9	8.8 [†]
7.1	90	5.9	12.6 [†]
12.1	88	4.6	14.2
14.3	105	6.5	10.9
14.9	93	7.1	11.2
17.0	94	7.7	11.3
17.1	87	6.7	12.2
18.5	87	5.6	14.3
20.3	112	8.0	8.5
22.0	108	4.7	11.1
23.7	118	6.3	8.1
24.0	95	5.6	11.5
24.4	94	6.6	11.5
25.0	92	2.5	12.3
27.0	89	9.0	11.2
27.4	104	3.6	11.9
27.4	122	6.0	8.6
28.3	119	5.5	9.5
29.4	105	3.5	9.7
35.0	100	5.1	10.4
35.9	119	3.4	8.9

Note.—The means for gestational age, maternal perimeter, fetal depth, and normalized fetal dose were 19.7 weeks, 101 cm, 6.1 cm, and 10.8 mGy/100 mAs, respectively.

* Uterus dose was calculated because the fetus and gestational sac were not visible.

[†] Gestational sac dose was calculated because the fetus was not visible.

Table 2

Radiation Dose to Fetus as Estimated with Monte Carlo Technique Compared with That of Three Existing Fetal Dose Estimation Techniques

Dose Estimation Method	No. of Patient Models	Normalized Fetal Dose (mGy/100 mAs)	
		Average	Range
Monte Carlo	24	10.8	7.3–14.3
Felmler et al (1) (recommended $\pm 20\%$ size range)	1	11.3	9.0–13.6
ImPACT	1	12.0	NA
CT-Expo	1	11.7	NA

Note.—NA = not applicable.

this study. However, there are several existing fetal dose estimation methods against which the results of this study can be compared.

The first comparison method for the

estimation of fetal dose was that of Felmler et al (1). For these calculations, the fetus was assumed to be axially centered, and contiguous axial scans were used instead of helical scans, with a pitch of 1.0.

Although this technique does not address gestational age and produces a single fetal dose result, Felmlee et al state that a dose estimate may vary by $\pm 20\%$ due to variations in patient size. The estimated fetal dose and a $\pm 20\%$ range were compared with the Monte Carlo results from this study. The abdomen of the anthropomorphic phantom used for the Felmlee technique had a perimeter of approximately 88 cm.

The second and third fetal dose estimation methods used for comparison were the ImPACT dose calculator (4) and CT-Expo software (7,8), which are both based on Monte Carlo simulations (5,10).

Figure 4

Figure 4: Graph of radiation dose to fetus versus gestational age. Gestational age does not significantly correlate with normalized fetal dose ($R^2 = 0.017$; $P = .543$).

Figure 5

Figure 5: Graph of radiation dose to fetus versus perimeter of mother. Perimeter of mother correlates linearly with normalized fetal dose ($R^2 = 0.681$; $P < .001$; standard error of the estimate = 1.053).

These methods were used to estimate dose to the uterus and represent fetal dose for gestational ages approximately less than or equal to 8 weeks in a standard-size patient. The perimeter of the hermaphrodite MIRD phantom used with the ImPACT software was approximately 99 cm at the pelvis (6). The Eva geometric phantom used with the CT-Expo software has an anteroposterior size of 18.8 cm (7) and an estimated perimeter of 93 cm. The ImPACT and CT-Expo software each produced a single fetal dose estimate, which was compared with the results from this study.

For each dose comparison method, the CT acquisition parameters (tube voltage, collimation, etc) were matched as closely as possible to the protocol simulated in this study. The scan length for the abdominal and pelvic examination was selected anatomically to span from the lower thorax to inferior of the pubic symphysis. This corresponded to a 50-cm scan length for the Felmlee technique, a 50-cm scan length for the ImPACT technique, and a 48-cm scan length for the CT-Expo technique.

Results

Dose Calculation

Table 1 shows the gestational age, perimeter of the mother, fetal depth, and the estimated fetal dose for each of the 24 patient models. The average fetal dose was 10.8 mGy/100 mAs $\pm$ 1.8 (standard deviation). The minimum, maximum, and median fetal doses were 7.3, 14.3, and 11.2 mGy/100 mAs, respectively.

Comparison with Existing Methods

The results of the existing methods are shown in Table 2; the Felmlee et al method produced estimates of 11.3 mGy/100 mAs (the $\pm 20\%$ range being equal to 9.0–13.6), while the ImPACT and CT-Expo methods yielded estimates of 12.0 and 11.7 mGy/100 mAs, respectively.

Regression Analysis

Fetal dose as a function of gestational age alone is shown in Figure 4. Linear

regression analysis ($R^2 = 0.017$) indicated no significant correlation ($r = -0.130$; $P = .543$) between gestational age and fetal dose.

Fetal dose as a function of the perimeter of the mother is shown in Figure 5; the relationship between the perimeter (P) (in centimeters) of the mother and fetal dose (DO_f) (in milligrays per 100 mAs) can be represented as:

$$DO_f = -0.122(P) + 23.11, \quad (1)$$

which has an R^2 value of 0.681, indicating a significant linear correlation ($r = -0.825$; $P < .001$) between maternal size and fetal dose. The standard error of the estimate for the perimeter model was 1.053.

A two-variable model including patient perimeter (in centimeters) and fetal depth (DE_f) (in centimeters) provides a better correlation with fetal dose (milligrays per 100 mAs), with an R^2 value of 0.799 ($r = -0.894$; $P = .002$). The two-variable model allows fetal dose to be estimated by:

$$DO_f = -0.119(P) - 0.029(DE_f) + 24.56. \quad (2)$$

The standard error of the estimate for the two-variable model was 0.855.

Discussion

Radiation dose to the fetus from multidetector CT imaging in pregnant patients was estimated for a range of actual pregnant patient anatomies, yielding a mean value of 10.8 mGy/100 mAs with a range of 7.3–14.3 mGy/100 mAs.

Patient size (perimeter) had a significant correlation with fetal dose ($P < .001$). This size metric was chosen because it can be easily measured in the clinic by using a tape measure around the estimated center of the fetus. The fetal depth also correlated well with fetal dose, resulting in a two-variable model for the estimation of fetal dose. Fetal depth may be measured on an ultrasonographic image of the patient or, if available, directly from a CT image.

There was no correlation between gestational age and fetal dose. There was insufficient information available on the height or weight of patients to investigate correlations of these patient size metrics with fetal dose.

When we compared existing dose estimation methods with the results of this study, we found that the Felmlee et al technique for the estimation of radiation dose produced a good estimate of fetal dose for an average-size patient. The ImPACT and CT-Expo fetal dose estimates were slightly conservative because fetal dose was slightly overestimated relative to that estimated with the methods and patient cohort used in this study. The estimates with the ImPACT and CT-Expo methods were still within the range of the doses estimated for the patients modeled in this study.

Of note, however, is that the results demonstrate a range of fetal doses that varied by nearly a factor of two (7.3–14.3 mGy/100 mAs) among the 24 patients modeled. This difference in fetal dose exceeded the range suggested by Felmlee et al.

The results from this study are reported as normalized dose per 100 mAs to allow for dose estimations of examinations with any tube current–time product. For example, for an examination with 300 mAs, the normalized results from this study should be tripled. The results can also be used to estimate fetal dose for CT protocols utilizing size-dependent tube current–time product settings. For example, the results for pregnant patients with larger perimeters can be scaled according to the tube current–time product settings for heavier or larger patients, and the results for patients with smaller perimeters can be scaled according to the tube current–time product settings for smaller patients.

Although the Monte Carlo simulations in this study are based on a single set of acquisition parameters, the results can be used to estimate dose for various protocols that differ in pitch, tube current (in milliamperes), or gantry rotation time (in seconds). To account for differences in pitch, dose

should be scaled proportional to the inverse of pitch (22). For example, to estimate the dose for an examination with a pitch of 1.375 (with all other technical parameters constant), the results from this study can be divided by 1.375.

To illustrate a dose calculation using all of the parameters that were found to be important in this study, consider an abdominal and pelvic helical CT examination in a pregnant patient with a perimeter of 101 cm and a fetal depth of 7 cm with the following acquisition protocol: GE LightSpeed 16, 120 kVp, pitch of 1.375, 300 mAs (220 effective mAs), and 16×1.25 -mm total nominal collimation. By substituting the mother's perimeter and the fetal location in Equation (2) and multiplying the result by a factor of 3 (300 mAs divided by 100 mAs) and dividing by the 1.375 pitch, one obtains a fetal dose of approximately 27 mGy. (Note that the gestational age is not a factor in this estimate.)

These results indicate that, while there may be wide variation among individual patients, fetal doses from a single abdominal and pelvic CT examination are still below the consensus levels or negligible risk (50–150 mGy) and well below the “actionable” level of 150 mGy (23). This should not be interpreted as CT imaging in pregnant patients should be performed without adequate clinical justification. It must also be considered that the dose estimates from this study represent a single CT acquisition. Many clinical examination protocols require two or three acquisitions (ie, pre- and postcontrast imaging), thus doubling or tripling the fetal dose.

There were several limitations to this study. While these methods did include an extensive set of voxelized patient models of pregnant patients, they may not be representative of the general population of all pregnant patients. While the cohort of patients used in this study spanned a range of gestational ages, the range of patient sizes encountered in clinical practice may be wider than those of the group presented here, and because perimeter correlated significantly with fetal dose, this could be important. Another limitation was that

only one multidetector CT scanner model was used in this study. We expect that there may be substantial differences in radiation dose per unit of tube current–time product with the various makes and models of CT scanners due to differences in x-ray beam filtration schemes. The differences between these schemes may not be easily taken into account; therefore, we are currently extending our Monte Carlo source models to those from other manufacturers. This study also simulated only constant tube current scans and therefore did not assess any dose savings that may be offered by using tube current modulation methods. This is also the subject of ongoing evaluations.

A method for the estimation of fetal dose from models of actual patient anatomy that represented a range of gestational age and patient size was developed. The mean fetal dose estimated across the patient cohort was 10.8 mGy/100 mAs, which is consistent with estimates from existing methods. However, the results from this study show a larger spread of values than previously recognized, thus demonstrating the importance of accounting for patient size in fetal dose estimates. Fetal dose correlated with maternal perimeter, and this correlation improved when both maternal size and fetal depth were accounted for.

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References

1. Felmlee JP, Gray JE, Leetzow ML, Price JC. Estimated fetal radiation dose from multislice CT studies. *AJR Am J Roentgenol* 1990; 154(1):185–190.
2. Shope TB, Gagne RM, Johnson GC. A method for describing the doses delivered by transmission x-ray computed tomography. *Med Phys* 1981;8(4):488–495.
3. Hurwitz LM, Yoshizumi T, Reiman RE, et al. Radiation dose to the fetus from body MDCT during early gestation. *AJR Am J Roentgenol* 2006;186(3):871–876.
4. ImPACT CTDosimetry. Imaging performance assessment of CT scanners: a medical devices agency evaluation group. CT scanner matching data, tables of CTDI values in air, CTDI_w, and phantom factor val-

- ues. ImPACT Internet home page. <http://www.ImPACTscan.org>. Accessed August 2000.
- Jones DG, Shrimpton PC. Survey of the practice in the UK. III. Normalized organ doses calculated using Monte Carlo techniques. NRPB R-250. Chilton, England: National Radiological Protection Board, 1991.
 - Snyder WS, Fisher HL, Ford MR, et al. Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom. *J Nucl Med* 1969;(supp 3):7-52.
 - Stamm G, Nagel HD. CT-expo: a novel program for dose evaluation in CT [in German]. *Rofo* 2002;174(12):1570-1576.
 - Nagel HD. Radiation exposure in computed tomography, fundamentals, influencing parameters, dose assessment, optimisation, scanner data, terminology. COCOR European Coordination Committee of the Radiological and Electromedical Industries, 2nd ed (in English, revised and translated by Nagel HD and Shrimpton PC). Hamburg, Germany: Paul Hartung Druck, 2000.
 - Kramer R, Zankl M, Williams G, Drexler G. The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods. I. The male (Adam) and female (Eva) adult mathematical phantoms. Neuherberg, Germany: GSF-Bericht, 1982;S-885.
 - Zankl M, Panzer W, Drexler G. The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods. VI. Organ doses from computed tomographic examinations. GSF report 30/91. Oberschleissheim, Germany: GSF-Forschungszentrum, 1991.
 - Shi C, Xu XG. Development of a 30-week-pregnant female tomographic model from computed tomography (CT) images for Monte Carlo organ dose calculations. *Med Phys* 2004;31(9):2491-2497.
 - Osei EK, Faulkner K. Fetal position and size data for dose estimation. *Br J Radiol* 1999;72(856):363-370.
 - DeMarco JJ, Solberg TD, Smathers JB. A CT-based Monte Carlo simulation tool for dosimetry planning and analysis. *Med Phys* 1998;25(1):1-11.
 - Jarry G, DeMarco JJ, Beifuss U, Cagnon CH, McNitt-Gray MF. A Monte Carlo-based method to estimate radiation dose from spiral CT: from phantom testing to patient-specific models. *Phys Med Biol* 2003;48(16):2645-2663.
 - DeMarco JJ, Cagnon CH, Cody DD, et al. A Monte Carlo based method to estimate radiation dose from multidetector CT (MDCT): cylindrical and anthropomorphic phantoms. *Phys Med Biol* 2005;50(17):3989-4004.
 - Staton RJ, Lee C, Lee C, et al. Organ and effective doses in newborn patients during helical multislice computed tomography examination. *Phys Med Biol* 2006;51(20):5151-5166.
 - DeMarco JJ, Cagnon CH, Cody DD, et al. Estimating radiation doses from multidetector CT using Monte Carlo simulations: effects of different size voxelized patient models on magnitudes of organ and effective dose. *Phys Med Biol* 2007;52(9):2583-2597.
 - Lee C, Lee C, Staton RJ, et al. Organ and effective doses in pediatric patients undergoing helical multislice computed tomography examination. *Med Phys* 2007;34(5):1858-1873.
 - Waters L, ed. 2002 MCNPX user's manual, version 2.4.0. Los Alamos National Laboratory report LA-CP-02-408. 2002.
 - Waters L, ed. 2003 MCNPX user's manual, version 2.5.C. Los Alamos National Laboratory report LA-UR-03-2202. 2003.
 - Hubbell JH, Seltzer SM. Tables of x-ray mass absorption coefficients and mass energy-absorption coefficients (version 1.03). <http://physics.nist.gov/>. Gaithersburg, Md: National Institute of Standards and Technology. 1995.
 - McNitt-Gray MF. AAPM/RSNA physics tutorial for residents: topics in CT—radiation dose in CT. *RadioGraphics* 2002;22(6):1541-1553.
 - McCollough CH, Schueler BA, Atwell TD, et al. Radiation exposure and pregnancy: when should we be concerned? *RadioGraphics* 2007;27(4):909-917.

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