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Reference Dataset for Benchmarking Fetal Doses Derived from Monte Carlo Simulations of CT Exams

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Abstract

Purpose—Task Group Report 195 of the American Association of Physicists in Medicine contains reference datasets for the direct comparison of results among different Monte Carlo (MC) simulation tools for various aspects of imaging research that employs ionizing radiation. While useful for comparing and validating MC codes, that effort did not provide the information needed to compare absolute dose estimates from CT exams. Therefore, the purpose of this work is to extend those efforts by providing a reference dataset for benchmarking fetal dose derived from MC simulations of clinical CT exams.

Acquisition and Validation Methods—The reference dataset contains the four necessary elements for validating MC engines for CT dosimetry: (1) physical characteristics of the CT scanner, (2) patient information, (3) exam specifications, and (4) fetal dose results from previously validated and published MC simulations methods in tabular form. Scanner characteristics include non-proprietary descriptions of equivalent source cumulative distribution function (CDF) spectra and bowtie filtration profiles, as well as scanner geometry information. Additionally, for MCNPX MC engines, normalization factors are provided to convert raw simulation results to absolute dose in mGy. The patient information is based on a set of publicly available fetal dose models and includes de-identified image data; voxelized MC input files with fetus, uterus, and gestational sac identified; and patient size metrics in the form of water equivalent diameter (D_w) z-axis distributions from a simulated topogram ($D_{w,topo}$) and from the image data ($D_{w,image}$). Exam characteristics include CT scan start and stop angles and table and patient locations, helical pitch, nominal collimation and measured beam width, and gantry rotation time for each simulation. For simulations involving estimating doses from exams using tube current modulation (TCM), a realistic TCM scheme is presented that is estimated based upon a validated method. (4) Absolute

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and $CTDI_{vol}$-normalized fetal dose results for both TCM and FTC simulations are given for each patient model under each scan scenario.

Data Format and Usage Notes—Equivalent source CDFs and bowtie filtration profiles are available in text files. Image data are available in DICOM format. Voxelized models are represented by a header followed by a list of integers in a text file representing a three-dimensional model of the patient. Size distribution metrics are also given in text files. Results of absolute and normalized fetal dose with associated MC error estimates are presented in tabular form in an Excel spreadsheet. All data are stored on Zenodo and are publicly accessible using the following link: https://zenodo.org/record/3959512.

Potential Applications—Similar to the work of AAPM Report 195, this work provides a set of reference data for benchmarking fetal dose estimates from clinical CT exams. This provides researchers with an opportunity to compare MC simulation results to a set of published reference data as part of their efforts to validate absolute and normalized fetal dose estimates. This could also be used as a basis for comparison to other non-MC approaches, such as deterministic approaches, or to commercial packages that provide estimates of fetal doses from clinical CT exams.

Keywords

Computed tomography; Monte Carlo simulations; benchmarking; fetal dose

1. INTRODUCTION

Monte Carlo (MC) simulation methods have been a mainstay for estimating dose to radiosensitive organs from Computed Tomography (CT) for well over two decades.[1–6] With the MC method, the patient anatomy is usually represented as some type of computational anatomic model (e.g., geometric or voxelized) and the CT scanner is usually characterized by the x-ray spectra leaving the tungsten anode of the CT x-ray source. The transportation of ionizing radiation is simulated through a virtual representation of patient anatomy and CT scanner output. The versatility afforded by most MC engines allows for a vast assortment of clinical situations to be performed as an attractive, reliable alternative to physical measurements involving patients (or cadavers).[7–11] Many MC-based methods are commercially available through dose management software packages and are widely used clinically. In addition, the reduction of cost of computational power and the increase in the availability of high-performance computing assures that the MC simulation approach will remain an important facet of CT dosimetry for the foreseeable future.[12]

Despite the flexibility, reliability, and availability offered by the MC simulation approach, the results of these calculations must nevertheless be validated to ensure their accuracy.[13,14] Validation processes for MC calculations are, however, not trivial, and typically involve one of two approaches.[15] One approach to validation involves replicating the conditions of a physical experiment within an MC engine, and comparing the simulation results to those of the physical experiments. This approach, though, hinges on the mathematical representation of the physical conditions accurately reflecting the details of the experimental setup, such that the differences between the two are minimized. Even with

simple geometries and experimental conditions, the replication of experimental conditions and physical results using MC engines can be difficult.

The other approach requires benchmarking MC results against previously published simulations. This approach poses another set of challenges. The first challenge is that a relevant set of simulations has to exist in order for there to be a meaningful comparison. The next challenge is that, even should a pertinent set of simulations exist, there is often an insufficient amount of detail in the descriptions of the simulation in order to accurately mirror the conditions of the original simulation. Lastly, the published form of the results is often not expressed in formats that are amenable to direct comparison, being either summarized or represented graphically.

Task Group Report 195 of the American Association of Physicists in Medicine provides researchers tools to validate MC simulation packages by providing a set of reference simulations for various scenarios related to imaging research utilizing ionizing radiation.[15] Included with these reference simulations are complete descriptions of simulation conditions and the results from four widely-used MC engines in tabular form.[15] Specifically, Case #5 of AAPM Report 195 is concerned with the benchmarking of photon transport and interactions through a complex, voxelized, reference object (XCAT phantom[16]) from a rotating x-ray source, a configuration characteristic of CT dosimetry.[15] Exposures of the reference voxelized model were performed with two different beam energies and at various projection angles. The energy deposition in all the voxels corresponding to either soft tissue, organ, or cortical bone was scored for each exposure in terms of eV per simulated photon with associated statistical uncertainties for each voxel type.[15] While this configuration and the presentation of the results is a step forward for benchmarking the results from different MC codes, there were several limitations to that work. One was that the scenarios were constructed to facilitate ease of comparison of codes and that the clinical scenarios were somewhat idealized; specifically, scenario #5 used a source with no bowtie filtration. In addition, the organ doses were presented as absorbed energy per simulated photon in each voxel, which meant there was no ability to estimate the absolute value of organ dose from a clinical scan.

Therefore, in an effort to extend the work of AAPM Report 195, the purpose of this dataset is to provide a set of previously validated and published reference simulations. This will allow researchers to validate their absolute and $CTDI_{vol}$-normalized organ dose calculations from MC methods that are reflective of a clinical CT exam. In addition, the datasets can also be viewed as a learning tool, since they show the various items that need to be considered when a researcher would like to simulate a clinical CT system for dosimetry investigations. The specific clinical scenario used in this work is estimating the dose to the fetus when a CT Abdomen/Pelvis exam is performed on a pregnant patient. This dataset contains the four necessary elements for absolute and normalized fetal dose estimation: (1) physical characteristics of a CT scanner, (2) patient (and fetus) information, (3) clinical CT exam specifications, and (4) fetal dose results in tabular form from previously validated and published MC simulations methods.

2. ACQUISITION AND VALIDATION METHODS

The clinical CT exam scenarios described in this dataset are all based on the publication of Hardy et al.[17] The scanner characteristics within the dataset are based on the work of Turner et al.[18] Specifically, the scanner and exam characteristics are based on one CT scanner (Definition AS64, Siemens Healthineers, Forchheim, Germany) described in Hardy et al.[17] The patient information supplied by this dataset are the pregnant patient models used in the fetal dose studies conducted by Angel et al.[8] The exam specification and reference simulations are based on the scanner characteristics, exam specifications and fetal dose results used in the Hardy et al.[17] study. In that study, absolute fetal dose expressed in mGy and $CTDI_{vol}$-normalized fetal dose were estimated for both tube current modulated (TCM) and fixed tube current (FTC) scans using the aforementioned pregnant patient models. Additionally, scanner data for supplemental FTC simulations unrelated to the Hardy et al. study are included in the dataset. The contents of this reference dataset will therefore allow researchers to validate their MC simulation approaches for absolute fetal dose in terms of mGy and $CTDI_{vol}$-normalized fetal dose.

2.1 Scanner characteristics

The scanner characteristics concerning the x-ray source and bowtie filtration provided in this dataset are from the “equivalent source” and “equivalent bowtie” methods outlined in Turner et al.,[18] and, as such, are non-proprietary. In total, the “equivalent source and filtration” descriptions are provided for four different scenarios, including with and without tube current modulation, as well as two additional kV settings. The first two scenarios—Scenarios A) and B)—are based on the simulations performed in Hardy et al., which is based on the 120 kV beam and “Body” (W1) bowtie. Scenario A is the TCM scans, while Scenario B is FTC scans (see Sec. 2.3). Additionally, two sets of FTC supplementary simulations are provided in the dataset: C) 140 kV beam with the “Body” (W1) bowtie and D) 100 kV beam with the “Head” (W2) bowtie. Scenarios C and D are included to provide additional scanning conditions and may not necessarily represent clinically-relevant scanning scenarios. The “equivalent sources” are all given in the form of a cumulative distribution function (CDF) for incorporation into an MC engine. All of the “equivalent bowtie” filter profiles are given in terms of path lengths of aluminum across one half of the fan angle.[18]

The source-to-image distance (SID) and fan angle for the bowtie filter are also provided for the scanner. Concerning radiation output metrics, the air kerma measurements from a Farmer chamber positioned at isocenter and $CTDI_{vol}$ per tube current-exposure time product (henceforth mAs) for a 32 cm diameter PMMA phantom are both presented. Additionally, the normalization factor ($NF_{E,T}$)[4] is provided for MC engines that report energy deposition tallies per source particle (such as MCNPX[19]). $NF_{E,T}$ is dependent on the scanner, beam energy, and bowtie filter and is used to convert the raw MCNPX dose tally output into units of absolute dose (see Sec. 2.5). Since $NF_{E,T}$ is dependent on beam energy and bowtie filter, the $NF_{E,T}$ values for all of the above scenarios are provided.

2.2 Patient Information

2.2.1 Anonymized patient image data—The patient information contained in this dataset is comprised of the pregnant models used for the studies on fetal dose conducted by Angel et al.[8] and subsequently by Hardy et al.[17] The patient cohort includes 24 pregnant patients of gestational ages ranging from less than 5 weeks to 35.9 weeks, who were administered clinically-indicated abdominal/pelvis CT examinations. The image thickness ranged from 1.25 mm to 10 mm. All of the images contained the patient anatomy from the lower thorax to the pubic symphysis, including the entirety of the uterus, gestational sac, and the fetus, depending on the gestational age. For these image data, the uterus, gestational sac, and fetus (if present) were semi-manually segmented in order to create the voxelized phantom models described in Sec 2.2.2.

2.2.2 Voxelized patient models—The patient models contained in the dataset are represented as a three-dimensional array of integers, accompanied by a header wherein the geometry of the model is specified.[19] The integers are tissue identification codes which correspond to material designation of tissue types. The tissue designations for each integer used to make the patient models are shown in Table I. The material descriptions are based on elemental composition and tissue densities as defined in ICRU Report 44.[3,20] Figure 1 displays an example of one of the voxelized models from the segmented image data. Table II shows the characteristics of all the voxelized models included in the dataset.

2.2.3 Patient size descriptions—Patient size estimates are important and were necessary for the predictive models of fetal dose developed in Hardy et al.[17] and for the size-specific dose estimates (SSDEs).[21] The reference dataset therefore includes two distributions of water equivalent diameter along the z-axis ($D_w(z)$) for each pregnant patient model. The first distribution of D_w is calculated from the image data, $D_{w,image}(z)$, using the methods specified in AAPM Report 220 for calculating D_w using CT numbers.[21] The second distribution of D_w(z) was generated from a simulated CT radiograph (which Siemens calls the “topogram”) of the voxelized image data for each patient, in accordance to the methods described in McMillan et al.[22] In this case, $D_{w,topo}$ as a function of table position, z, is calculated as

$$D_{w,topo}(z) = \sqrt{AP(z) \times LAT(z)}. \quad (1)$$

Where $AP(z)$ and $LAT(z)$ represent the total antero-posterior and lateral water-equivalent attenuation estimates, respectively, at each table position z along the entire scan length of the patient.[21,22] $AP(z)$ and $LAT(z)$ were used to generate the estimated TCM profiles mentioned in Sec. 2.3. Figure 2 shows the AP, lateral, and $D_{w,topo}$ distributions generated from the simulated topogram as a function of table position. For both distributions, D_w estimates taken at the center of the scan volume (z=center) and at the three-dimensional geometric center of the fetus (z=centroid), the same location used in Angel et al.[8] and Hardy et al.[17], are provided in the dataset.

2.3 Exam Specifications

The exam specifications used in the study on TCM and FTC fetal dose conducted by Hardy et al. comprise the simulation Scenarios A and B as discussed in Sec. 2.1. The scanning parameters for both scenarios are given in Table III.[17] For TCM simulations, the tube current information provided in the data set is based on the methodology developed by McMillan et al.[22] This method approximates the TCM algorithm of one manufacturer (CAREDose4D[23], Siemens Healthineers, Forchheim Germany), and provides the tube current information in a format similar to the TCM data as extracted from raw projections. Specifically, for each patient, the tube current information (given in mA, as illustrated in Figure 3 below), I, is expressed as a function of table position and tube angle, $I(z, \Theta)$, where z represents the table position and Θ is the tube angle within the gantry.[7] The complete TCM scheme is provided for each patient. $\Theta = 0°$ defines the 3 o'clock position along the positive x-axis with the direction of rotation being clockwise around the positive y-axis. For incorporation into MCNPX, all values of $I(z, \Theta)$ for each patient were normalized by the maximum tube current (which is also provided separately) to obtain normalized tube current values that range from 0 to 1; these normalized tube current values were used as weighting factors in MCNPX.[24] Furthermore, as discussed in Sec. 2.1, the exam specifications for the two supplementary FTC simulations, Scenarios C and D, are given in Table IV. Simulations for Scenarios C and D were only performed on five of the fetal dose patient models.

$CTDI_{vol}$ values are based on the $CTDI_{vol}$ per mAs (mGy/mAs) measurements mentioned previously in Sec. 2.1 for the AS64 scanner. For TCM, the $CTDI_{vol}$ values were derived for each TCM curve based on the average mA across the scan. Thus, for TCM scans, the average tube current for each patient is also provided. For FTC, the $CTDI_{vol}$ value is based on the effective mAs. The scan lengths used for each voxelized model are listed in Table II. In the materials provided in the reference dataset, the CT scan start (x-ray beam on), scan stop (x-ray beam off) and start angle are all provided for each patient and for each type of exam. An example of the TCM scheme using the scanning parameters in Table III is shown in Figure 3.

2.4 MC simulation specifications

The MC simulation specifications are those that were used in the Hardy et al. study. The MC software package used in the Hardy et al. study was a modified version of MCNPX (Monte Carlo N-Particle eXtended version 2.7.a.[25,26] The modifications allowed MDCT scanner geometries, spectra, and filtration data to be incorporated.[1,2,4,27,28] All simulations were conducted in photon transport mode with a 1 keV low-energy cut-off, and all photoelectrons were assumed to deposit their energy locally. All simulations were performed with 10^7 particle histories with the center of the voxelized patient models at isocenter. The estimated statistical uncertainties reported by MCNPX for fetal dose values were below 1% for all but two cases, which had statistical uncertainties of less than 2%. Validation of this modified MCNPX simulation package has been reported, including with TCM.[1,29–31] The MCNPX simulations were conducted using the computational and storage services associated with the Hoffman2 Shared Cluster provided by UCLA Institute for Digital Research and Education's Research Technology Group.

2.5 Tabular absolute and $CTDI_{vol}$-normalized fetal dose estimates

The dose values included in the dataset are from published results of TCM and FTC fetal doses from Hardy et al. (Scenarios A and B).[17] In addition, the dose values for the supplementary Scenarios C and D are also given. The fetal dose results for both TCM and FTC simulations presented in this dataset are from the *F4 energy fluence tally of MCNPX, which records energy fluence on a per voxel basis (MeV/cm^2/photon). The *F4 tally results were then used in conjunction with "DE" (dose energy) and "DF" (dose function), which multiplied the energy fluence values by the energy-dependent mass absorption coefficient values published by Hubbell and Seltzer[32]. As such, the results of the *F4 tally with the DE and DF cards convert fluence values to dose values, both on a per voxel basis (MeV/g/photon).[19] Fetal doses are then obtained by averaging the dose to the voxels comprising the fetal volume. The number of simulated photons, the raw MCNPX output from the *F4 tally with the DE and DF cards, and the statistical uncertainty of the *F4 tally for each patient are provided for all simulation scenarios. In order to convert the raw MCNPX tally results to mGy per mAs, the results of *F4 tally results with the DE and DF cards were multiplied by the normalization factor ($NF_{E,T}$) mentioned in Sec 2.1. It should be noted that the number of photons in the definition of the $NF_{E,T}$ refers to the photons that are emitted within the fan beam.

To estimate absolute fetal dose in mGy for TCM scans, the normalized MCNPX output from *F4 tally with the DE and DF cards were multiplied by the maximum mAs for each patient. As mentioned in Sec. 2.3, MCNPX was modified to use normalized tube current values as weighting factors applied to the photons at emission. Because the rotation time is constant throughout the scans, the *F4 tally output after the application of $NF_{E,T}$ can be scaled by the maximum tube current-exposure time product (in mAs). To estimate absolute dose for FTC scans, the *F4 tally output after the application of $NF_{E,T}$ was multiplied by the effective mAs. For both TCM and FTC scans, $CTDI_{vol}$-normalized dose values were calculated by dividing absolute doses by the $CTDI_{vol}$ values for each patient. Figure 4 outlines the process to estimate absolute and $CTDI_{vol}$-normalized fetal dose from Hardy et al.

3. DATA FORMATS AND USAGE NOTES

3.1 Scanner characteristics

For the scanner characteristics, all "equivalent source" CDFs are given as texts file which contains a single column of cumulative probabilities binned in 1 keV increments starting at 1 keV (top of bin) energy and up to 140 keV (hence, 140 entries). The bowtie filtration profiles are also text files consisting of two columns. The first column consists of the equivalent path length of aluminum (in cm) while the second column contains the corresponding fan half-angle (in degrees). The geometric properties of the scanner, the SID and fan angle, are given in the Excel spreadsheet containing the MCNPX simulation results detailed below in Sec. 3.4. Additionally, the radiation output characteristics mentioned in Sec. 2.1, namely, the physical air kerma measurements taken at isocenter with a 100 mm pencil ion chamber and $CTDI_{vol}$ per mAs values, are included in the same Excel spreadsheet. Lastly, both simulated air kerma values (given in MeV/g/source particle and in

mGy/mAs) and the $NF_{E,T}$ for this scanner, tube voltage, and bowtie are also provided in the Excel spreadsheet.

3.2 Patient Information

The image data for each patient is contained in a directory wherein the anonymized DICOM images from the original CT exam of the patient are ZIP compressed. The voxelized models are provided as MCNPX input files, which are text files composed of a header followed by a two-dimensional array of integers that correspond to the material designations outlined in Table I. The beginning of the file also contains the voxel dimension specification (in cm), material specifications, and F4 tally specifications. By default, all voxelized models are centered about the source-to-isocenter distance (SID) in the x-y plane and in the z direction. $D_{w,topo}(z)$ is presented in a comma-delimited text file in which each column contains the table position (z, in mm, from the simulated topogram performed at 1 mm increments[17,22]), $AP(z)$, $LAT(z)$, and $D_w(z)$ (in cm), respectively, from the simulated topogram. $D_{w,image}(z)$ is given as a single-column text file with D_w estimates from each image in the series wherein each entry in the file is the D_w estimate for each image slice. $D_{w,topo}(z=\text{center})$, $D_{w,topo}(z=\text{centroid})$, $D_{w,image}(z=\text{center})$, and $D_{w,topo}(z=\text{centroid})$ estimates for each patient are all included in the Excel spreadsheet containing the simulation results.

3.3 Exam Specifications

The $I(z, \Theta)$ profile is given in a text file. The first row of the text file corresponds to the total number of projections (i.e., the total number of entries). The remainder of the text file contains columns of the table positions (in cm), the corresponding tube gantry angles (in degrees), and tube current values (in mA). For each patient, the scan start and stop location along the length of the voxelized model used for the simulations are also given in the Excel spreadsheet. The maximum and average tube current from the TCM schemes are given in the Excel spreadsheet for each patient. The maximum tube current value is used to calculate units of absolute fetal dose in mGy described below in Sec 3.4. For TCM, the $CTDI_{vol}$ values for each patient are also included in the Excel spreadsheet and are based on the average tube current and the $CTDI_{vol}$ per mAs measurements. For FTC, the $CTDI_{vol}$ value is based on $CTDI_{vol}$ per mAs measurements multiplied by the effective mAs.

3.4 Tabular Results

The simulation results mentioned in Sec. 2.5 are tabulated for each of the four scenarios and for each patient in the Excel spreadsheet mentioned in the previous sections. The results of each simulation scenario are contained in four, separate, labeled tabs in the Excel spreadsheet. The results for each of the steps outlined in Sec. 2.5 and depicted in Figure 4 above are given in the Excel spreadsheet. Specifically, the raw MCNPX output from the *F4 tally with the DE and DF cards and the statistical uncertainty of the fetus tally (or the gestational sac tally or uterus tally, depending on the gestational age of the fetus) are reported in the spreadsheet. The raw MCNPX output for both TCM and FTC simulations was converted to units of dose using the $NF_{E,T}$ for the AS64 scanner, the tube voltage and the chosen bowtie filter. The normalized MCNPX output is referred as “Normalized MC Output” in the spreadsheet and is given in mGy/mAs for each patient. For TCM simulations, the absolute dose values in mGy for each patient were calculated by multiplying the

"Normalized MC Output" value by the maximum tube current value and the rotation time specified. For the FTC values, the "Normalized MC Output" was multiplied by the effective mAs. For both TCM and FTC simulations, the $CTDI_{vol}$-normalized doses were obtained by dividing the absolute dose values by the $CTDI_{vol}$ values. The raw MCNPX *F4 tally output with the DE and DF cards, "Normalized MC Output," absolute dose, and $CTDI_{vol}$-normalized dose values are all presented in the Excel spreadsheet for each patient. Figure 5 summarizes the components that are included in the reference data set.

4. DISCUSSION

The dataset introduced here is meant to serve as a logical continuation of the efforts of the AAPM Report 195 by providing a set of published simulation results using previously validated MC methods that researchers can use to benchmark absolute and $CTDI_{vol}$-normalized fetal doses from MC simulations. This dataset is not meant to be definitive in terms of fetal dose estimates. Given that estimates of fetal dose from CT currently rely heavily on MC methods and will continue to do so for the foreseeable future, the aim is to present the medical physics community with an avenue to directly assess their MC-derived fetal doses against published methods and results. This dataset also includes supplementary simulation results using previously published and validated methods. As such, the dataset provides the four necessary elements for CT dosimetry using MC methods, those being (1) scanner characteristics, (2) patient information, (3) exam specifications, and (4) absolute and $CTDI_{vol}$-normalized fetal dose results, in formats accessible to researchers.

This dataset contains non-proprietary CT source descriptions and filtration descriptions, as well as de-identified patient data and tabular fetal dose results. This dataset could serve as an open-source repository for non-proprietary scanner-beam spectra and filtration profiles. In addition, Figure 6 is a depiction of a potential workflow process that could be employed for benchmarking fetal dose results from an MC simulation package. For example, concerning fetal doses from a TCM scan, one could, starting with the (I) segmented image data,[8] incorporate into an MC engine the (II) voxelized phantom model,[8] (III) TCM data,[17,22] and (IV) scanner descriptors[18] and exam specifications to yield (VI) absolute fetal doses in mGy. The absolute fetal dose estimates from the MC engine could then be divided by the (V) $CTDI_{vol}$ estimates tabulated in the Excel spreadsheet. Both the (VI) absolute and (VII) $CTDI_{vol}$-normalized dose estimates from the MC engine could then be compared directly to the results provided in the dataset. MC results given in the dataset are both based on the TCM and FTC CT protocols outlined in Table III above. Therefore, one could, in principle, benchmark an MC engine using the simpler scenario of FTC and then progress to the more complex simulation scenario of TCM.

MC approaches for CT dosimetry have a long history and have even been developed or incorporated into commercial products, including patient dose management software products. This dataset could be used as a basis for comparison for researchers both using MC methods and developing new MC approaches. It could also be used to benchmark fetal dose estimates from commercial products. Along these lines, what is being provided could also be used to validate fetal dose estimates from a variety of methods not related to MC, such as deterministic methods.[33]

V. CONCLUSION

A publicly-available dataset of reference MC simulations for CT dosimetry with TCM and FTC has been developed for the medical physics community. The dataset is hosted on the Zenodo website under a Creative Commons Attribution 3.0 license, and, as such, it is free to download and use with no cost for scientific and educational purposes. This unique contribution will serve to give researchers interested in CT dosimetry the ability to benchmark fetal dose estimates from MC methods and quite possibly other methods, such as deterministic.

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REFERENCES

1. DeMarco JJ, Cagnon CH, Cody DD, Stevens DM, McCollough CH, O'Daniel J, 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. [PubMed: 16177525]
2. DeMarco JJ, Cagnon CH, Cody DD, Stevens DM, McCollough CH, Zankl M, 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):2583–97. [PubMed: 17440254]
3. Demarco JJ, Solberg TD, Smathers JB. A CT-based Monte Carlo simulation tool for dosimetry planning and analysis. Med Phys 1998;25:1–11. [PubMed: 9472820]
4. 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 [Internet] 2003;48(16):2645–63. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12974580
5. Group ImPACT. Imaging Performance Assessment of CT scanners.
6. Huda W, Atherton JV. Energy imparted in computed tomography. Med Phys [Internet] 1995;22(8):1263–9. Available from: 10.1118/1.597564
7. Angel E, Yaghmai N, Jude CM, Demarco JJ, Christopher H, Goldin JG, et al. Monte Carlo simulations to assess the effects of tube current modulation on breast dose for multidetector CT. Phys Med Biol 2010;54(3):497–512.
8. Angel E, Wellnitz CV, Goodsitt MM, Yaghmai N, DeMarco JJ, Cagnon CH, et al. 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 size. Radiology 2008;249(1):220–7. [PubMed: 18796678]
9. Zhang D, Savandi AS, Demarco JJ, Cagnon CH, Angel E, Turner AC, et al. Variability of surface and center position radiation dose in MDCT: Monte Carlo simulations using CTDI and anthropomorphic phantoms. Med Phys 2009;36(3):1025–38. [PubMed: 19378763]
10. Hardy AJ, Bostani M, McMillan K, Zankl M, McCollough C, Cagnon C, et al. Estimating lung, breast, and effective dose from low-dose lung cancer screening CT exams with tube current modulation across a range of patient sizes. Med Phys [Internet] 2018;45(10):4667–82. Available from: 10.1002/mp.13131
11. Hardy AJ, Bostani M, Hernandez AM, Zankl M, McCollough C, Cagnon C, et al. Estimating a size-specific dose for helical head CT examinations using Monte Carlo simulation methods. Med Phys [Internet] 2019;46(2):902–12. Available from: 10.1002/mp.13301

12. Sechopoulos I, Rogers DWO, Bazalova-Carter M, Bolch WE, Heath EC, McNitt-Gray MF, et al. RECORDS: Improved Reporting of montE CarlO RaDiation transport Studies: Report of the AAPM Research Committee Task Group 268. Med Phys 2018;45(1):e1–5. [PubMed: 29178605]
13. Long DJ, Lee C, Tien C, Fisher R, Hoerner MR, Hintenlang D, et al. Monte Carlo simulations of adult and pediatric computed tomography exams: Validation studies of organ doses with physical phantoms. Med Phys [Internet] 2013;40(1):13901 Available from: 10.1118/1.4771934
14. Bostani M, McMillan K, DeMarco JJ, Cagnon CH, McNitt-Gray MF. Validation of a Monte Carlo model used for simulating tube current modulation in computed tomography over a wide range of phantom conditions/challenges. Med Phys 2014;41(11):112101. [PubMed: 25370652]
15. AAPM Task Group 195. Monte Carlo Reference Data Sets for Imaging Research. College Park, MD: 2015.
16. Segars WP, Mahesh M, Beck TJ, Frey EC, Tsui BMW. Realistic CT simulation using the 4D XCAT phantom. Med Phys 2008;35(8):3800–8. [PubMed: 18777939]
17. Hardy AJ, Angel E, Bostani M, Cagnon C, McNitt-Gray M. Estimating fetal dose from tube current-modulated (TCM) and fixed tube current (FTC) abdominal/pelvis CT examinations. Med Phys [Internet] 2019;46(6):2729–43. Available from: 10.1002/mp.13499
18. Turner AC, Zhang D, Kim HJ, DeMarco JJ, Cagnon CH, Angel E, et al. A method to generate equivalent energy spectra and filtration models based on measurement for multidetector CT Monte Carlo dosimetry simulations. Med Phys 2009;36(6):2154–64. [PubMed: 19610304]
19. Pelowitz DB. MCNPX User's Manual. Version 2.7.0 Los Alamos National Laboratory, LA-CP-11–00438 Los Alamos, NM: 2011.
20. ICRU. Tissue Substitutes in Radiation Dosimetry and Measurement ICRU Rep No 44 1989;(ICRU, Bethesda, MD).
21. AAPM Task Group 220. Use of Water Equivalent Diameter for Calculating Patient Size and Size-Specific Dose Estimates (SSDE) in CT. College Park, MD: 2014.
22. McMillan K, Bostani M, Cagnon CH, Yu L, Leng S, McCollough CH, et al. Estimating patient dose from CT exams that use automatic exposure control : Development and validation of methods to accurately estimate tube current values. Med Phys 2017;44(August):4262–75. [PubMed: 28477342]
23. Flohr T CARE Dose4D White Paper. 2011.
24. Angel E, Yaghmai N, Jude CM, DeMarco JJ, Cagnon CH, Goldin JG, et al. Dose to radiosensitive organs during routine chest CT: Effects of tube current modulation. Am J Roentgenol 2009;193(5):1340–5. [PubMed: 19843751]
25. Pelowitz DB. MCNPX User's Manual Version 2.7.0, Los Alamos National Laboratory Report LA-CP-11–00438 (LANL, Los Alamos, NM, 2011). 2011.
26. AAPM (American Association of Physicists in Medicine). Monte Carlo Reference Data Sets for Imaging Research: The Report of AAPM Task Group 195. 2015.
27. Gatsonis CA, Aberle DR, Berg CD, Black WC, Church TR, Fagerstrom RM, et al. The national lung screening trial: Overview and study design. Radiology 2011;258(1).
28. Turner AC, Zhang D, Kim HJ, Demarco JJ, Cagnon CH, Angel E, et al. A method to generate equivalent energy spectra and filtration models based on measurement for multidetector CT Monte Carlo dosimetry simulations. Med Phys 2009;36(6).
29. Bostani M, Mueller JW, McMillan K, Cody DD, Cagnon CH, Demarco JJ, et al. Accuracy of Monte Carlo simulations compared to in-vivo MDCT dosimetry. Med Phys 2015;42(2).
30. Bostani M, McMillan K, Demarco JJ, Cagnon CH, McNitt-Gray MF. Validation of a Monte Carlo model used for simulating tube current modulation in computed tomography over a wide range of phantom conditions/challenges. Med Phys 2014;41(11).
31. Khatonabadi M, Zhang D, Mathieu K, Kim HJ, Lu P, Cody D, et al. A comparison of methods to estimate organ doses in CT when utilizing approximations to the tube current modulation function. Med Phys 2012;39(8):5212–28. [PubMed: 22894446]
32. Hubbell JH, Seltzer SM. Tables of X-Ray mass attenuation coefficients and mass energy-absorption coefficients [Internet]. Natl. Inst. Stand. Technol [cited 2019 5 13];Available from: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

33. Maslowski A, Wang A, Sun M, Wareing T, Davis I, Star-Lack J. Acuros CTS: A fast, linear Boltzmann transport equation solver for computed tomography scatter – Part I: Core algorithms and validation. Med Phys 2018;45(5):1899–913. [PubMed: 29509970]

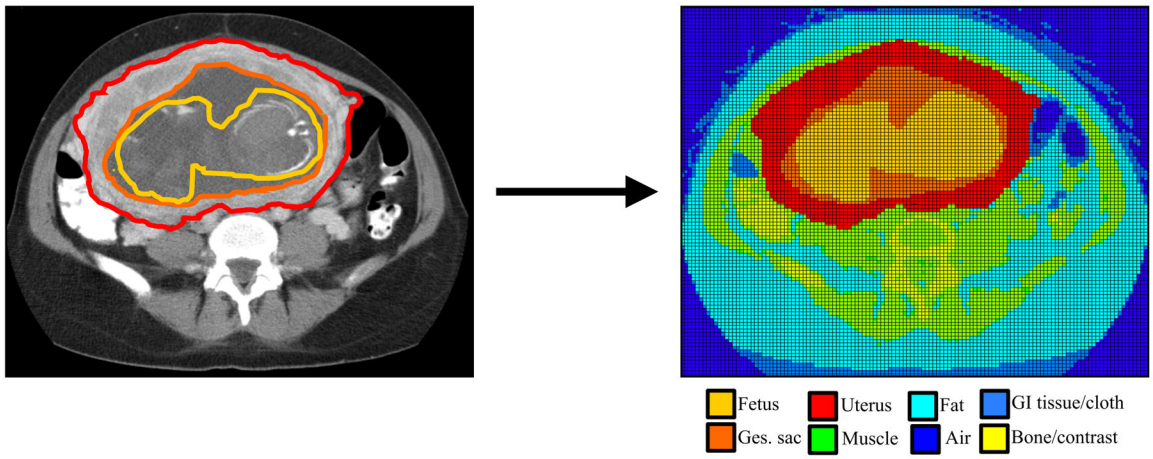

Figure 1:

(Left) Segmented image data of late-term pregnant patient delineating the uterus (red), gestational sac (orange), and fetus (amber). (Right) Subsequent voxelization of the segmented image data using the tisse codes shown in Table I. Note that the voxels of contrast enhanced regions are mapped to bone because of the high CT number.

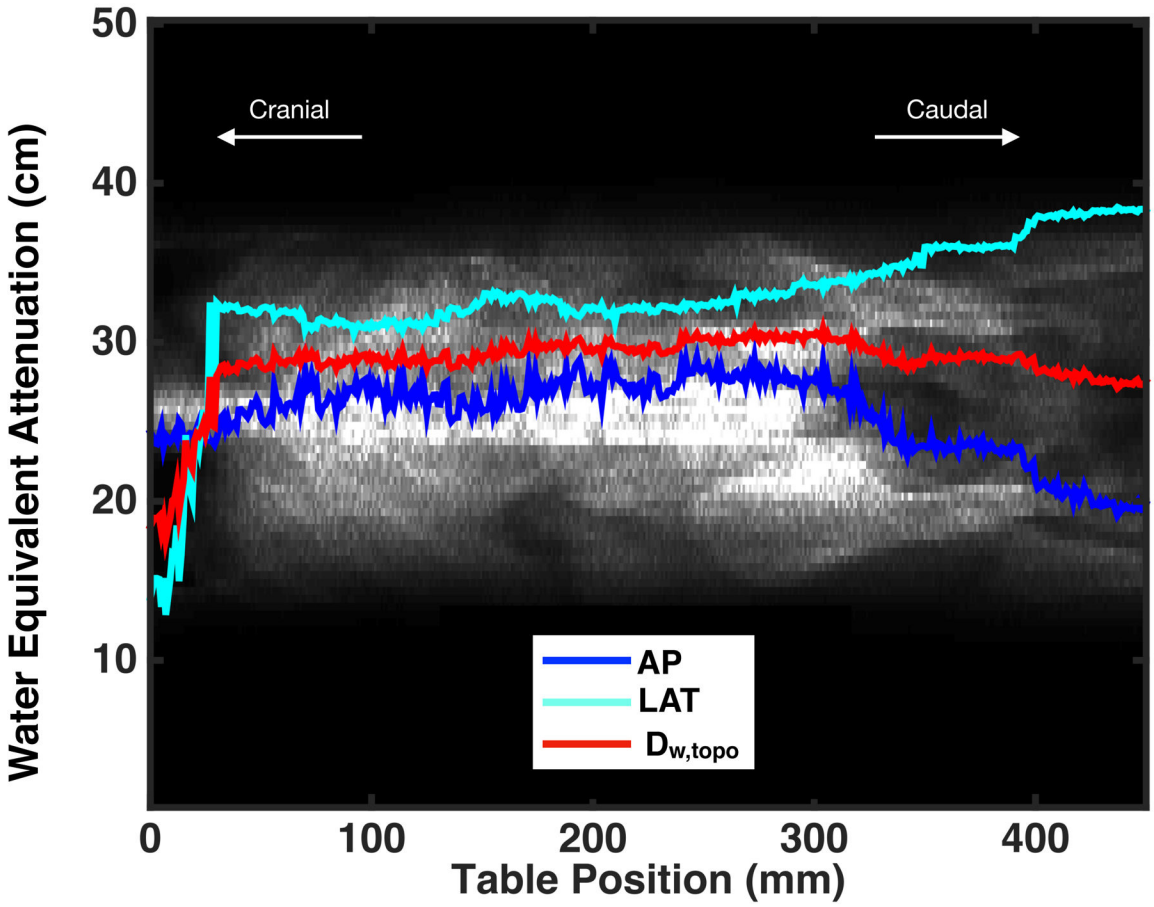

Figure 2:
The AP, lateral, and $D_{w,topo}$ as functions of table position overlaid atop of a simulated topogram of one of the pregnant patient models. All three distributions are provided in the data set.

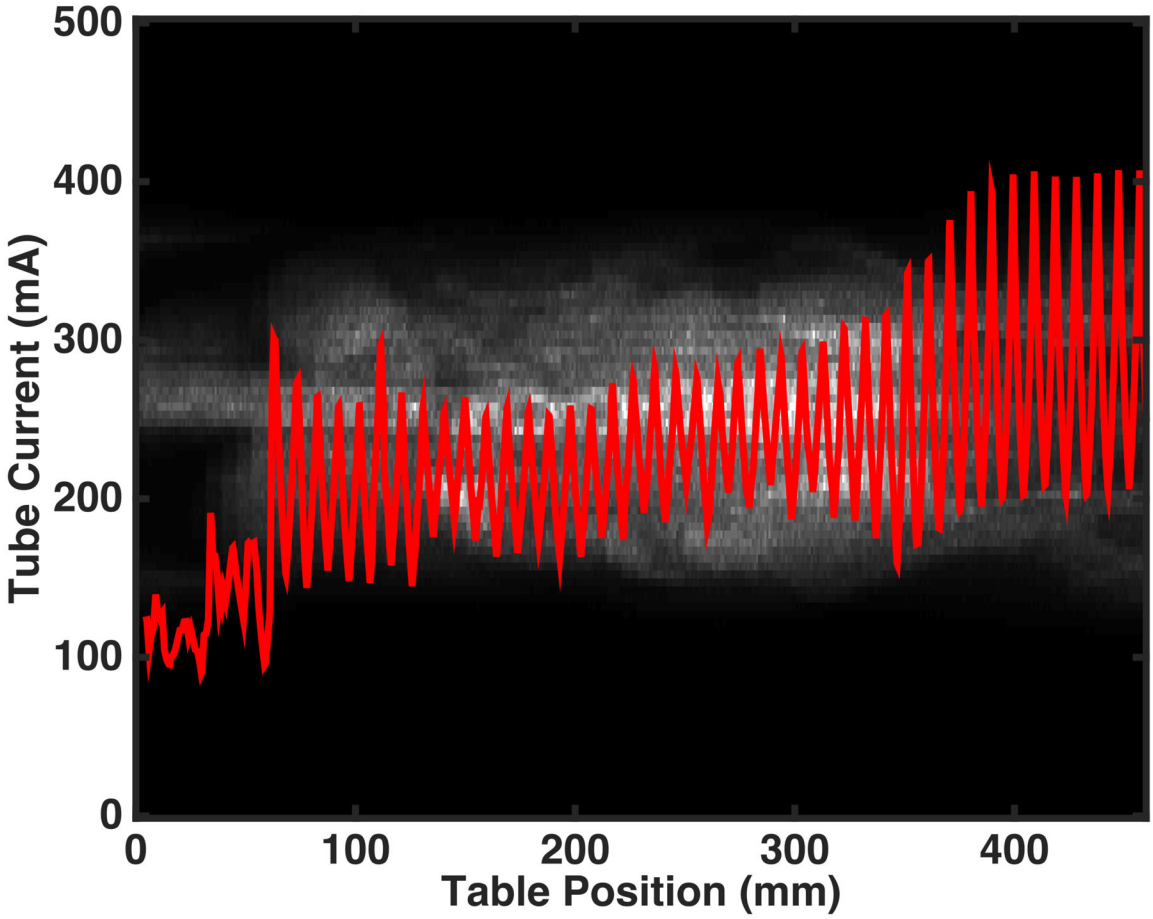

Figure 3:
Tube current as a function of table position overlaid on the simulated topogram of one of the pregnant patient models. The TCM profiles for all 24 pregnant patients are provided in the dataset.

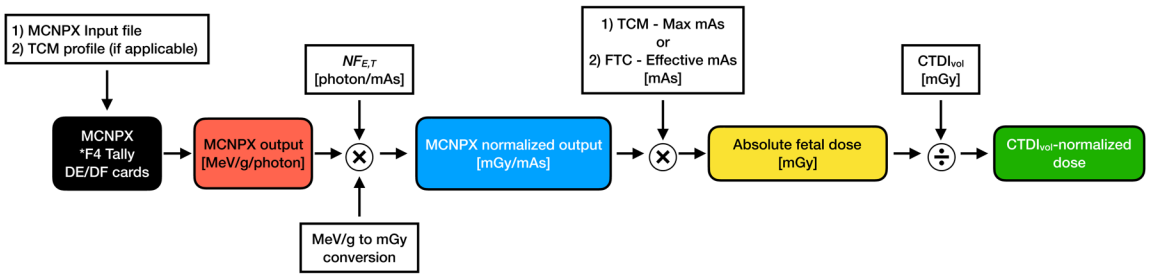

Figure 4:
Process of obtaining absolute and normalized fetal dose used by Hardy et al.

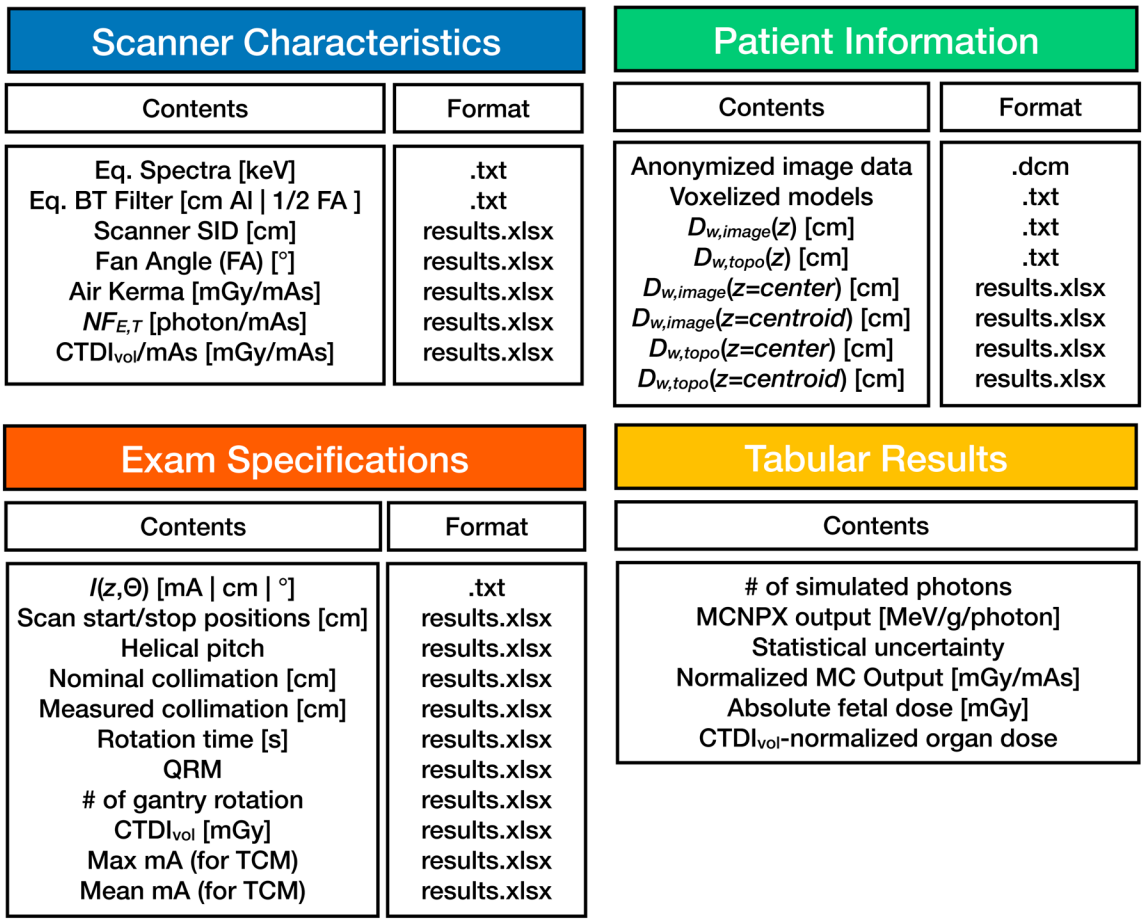

Figure 5:

Summary of the contents of the reference data set. The file formats of the scanner characteristics, patient information, and exam specification contents, and their associated units (where applicable), are given. Additionally, some elements of the scanner characteristics, patient information, and exam specifications are contained within the results.xlsx file.

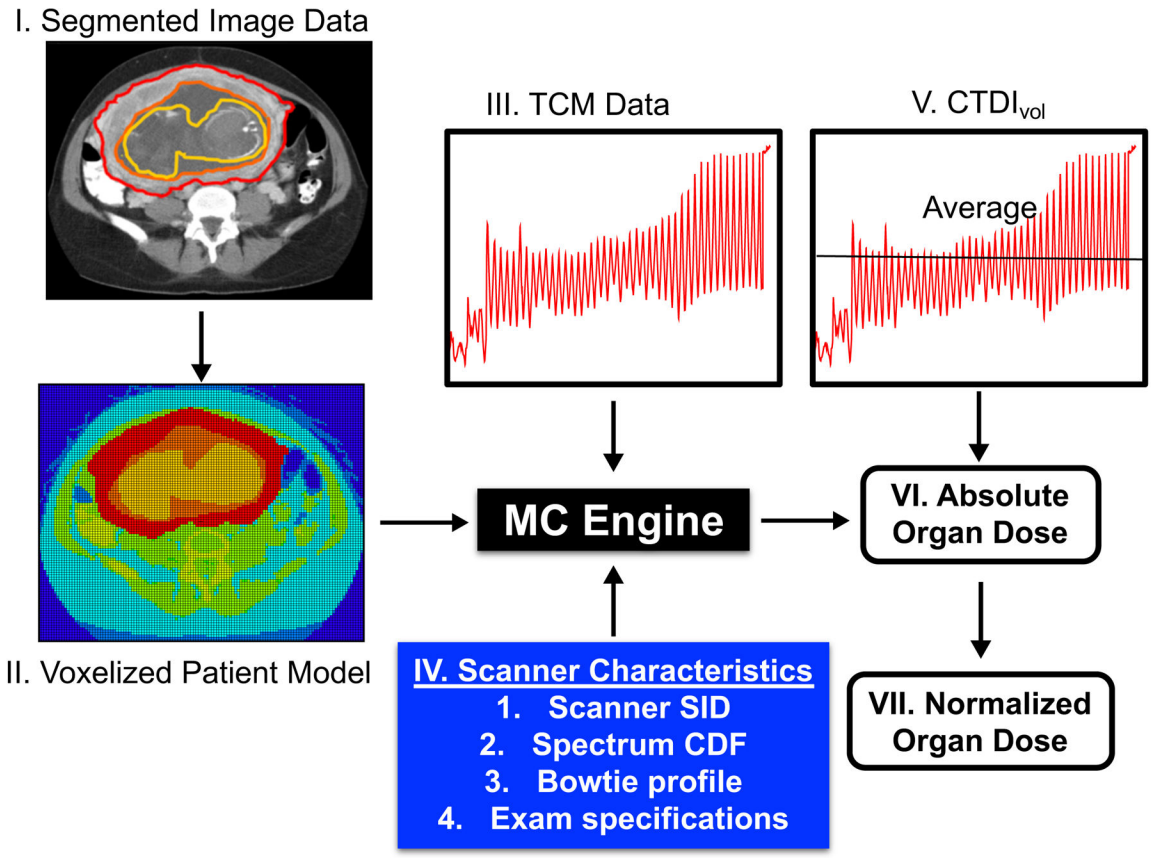

Figure 6:
Potential workflow process for this dataset for benchmarking an MC engine.

Table I:

Material designation used in the voxelized models

Tissue code	Material	Density (g/cm^3)
50	Air	0.00
51	Lung	0.05
52	Lung	0.13
53	Lung/cloth/GI tissue	0.30
54	Lung/cloth/GI tissue	0.47
55	Lung/cloth/GI tissue	0.65
56	Fat or soft tissue	0.85
57	Fat or soft tissue	0.93
58	Fat or soft tissue	0.98
59	Water	1.00
60	Muscle	1.06
61	Muscle	1.14
62	Muscle	1.26
63	Bone	1.48
64	Bone	1.68
65	Bone	1.89
66	Bone	2.10
89	Fetal bone	1.48
90	Fetal tissue	1.06
91	Gestational sac	1.00
92	Uterus	1.14

Table II:

Voxelized model resolution, voxel dimensions, and scan lengths for the 24 patient models included in the reference data set

Patient model	Gestational age (weeks)	Image slices	In-plane image size	Lateral voxel width (mm)	AP voxel width (mm)	Slice thickness (mm)	Scan length (cm)
Fetus13	< 5	107	128 × 128	3.2	3.2	5.0	53.5
Fetus24	5.0	87	128 × 128	2.4	2.4	5.0	43.5
Fetus26	5.0	89	128 × 128	2.4	2.4	5.0	44.5
Fetus16	6.6	91	128 × 128	2.8	2.8	5.0	45.5
Fetus10	7.1	84	128 × 128	2.4	2.4	5.0	42.0
Fetus7	12.1	62	128 × 128	2.4	2.4	5.0	31.0
Fetus6	14.3	94	128 × 128	2.8	2.8	5.0	47.0
Fetus9	14.9	88	128 × 128	2.4	2.4	5.0	44.0
Fetus22	17.0	85	128 × 128	2.4	2.4	5.0	42.5
Fetus2	17.1	92	128 × 128	2.4	2.4	5.0	46.0
Fetus31	18.5	177	128 × 128	2.4	2.4	2.5	44.3
Fetus19	20.3	49	128 × 128	2.8	2.8	10.0	49.0
Fetus28	22.0	92	128 × 128	2.8	2.8	5.0	46.0
Fetus12	23.7	81	128 × 128	2.8	2.8	5.0	40.5
Fetus4	24.0	69	128 × 128	2.4	2.4	7.0	48.3
Fetus3	24.4	94	128 × 128	2.4	2.4	5.0	47.0
Fetus11	25.0	125	128 × 128	2.8	2.8	3.75	46.7
Fetus35	27.0	347	128 × 128	2.4	2.4	1.25	43.4
Fetus5	27.4	100	128 × 128	2.8	2.8	5.0	50.0
Fetus17	27.4	107	128 × 128	3.2	3.2	5.0	53.5
Fetus18	28.3	111	128 × 128	3.2	3.2	5.0	55.5
Fetus15	29.4	98	128 × 128	2.8	2.8	5.0	49.0
Fetus14	35.0	71	128 × 128	2.8	2.8	7.0	49.7
Fetus20	35.9	90	128 × 128	3.6	3.6	5.0	45.0

Table III:

Scanning parameters used for Scenarios A and B, i.e., the TCM and FTC, respectively, scans on the Siemens Definition AS64 used in the Hardy et al. study.[17] The TCM protocol is based on CAREDose4D. FFS: flying focal spot.

Parameter	Scenarios A/B
Tube voltage (kV)	120
Quality Reference mAs (QRM)/Effective mAs	200/200
Rotation time (s)	0.5
Pitch	1.0
Nominal collimation (mm)	19.2 (64 × 0.6 FFS)
Measured collimation [FWHM] (mm)	23.8
Bowtie filter	Body (W1)
HVL (mm Al)	8.2
$CTDI_{vol}$ (mGy/mAs)	0.078

Table IV:

Scanning parameters for Scenarios C and D, i.e., the supplementary FTC simulations. Scenarios C and D may not be representative of clinically-relevant scanning scenarios. These protocols were only simulated for five of the fetal dose patient models.

Parameter	Scenario C	Scenario D
Tube voltage (kV)	140	100
Effective mAs	100	300
Rotation time (s)	0.5	1.0
Pitch	0.75	1.25
Nominal collimation (mm)	19.2 (64 × 0.6 FFS)	19.2 (64 × 0.6 FFS)
Measured collimation [FWHM] (mm)	23.8	23.8
Bowtie filter	Body (W1)	Head (W2)
HVL (mm Al)	9.2	7.2
$CTDI_{vol}$ (mGy/mAs)	0.116	0.037