

Article

Software Tool for Development of Personalized Computational Phantoms of Pregnant Patient in Computational Dosimetry Applications

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Abstract

When pregnant patients undergo diagnostic and therapeutic radiological procedures, the unborn child is exposed to an increased risk due to the use of ionizing radiation; therefore, the fetal dose must be estimated and optimized. Tools and methods routinely used for fetal dose estimation lack better personalization of patients. To address this, we developed a software tool for creating phantoms at different pregnancy stages and with varying patient anatomies to further personalize fetal dose estimation using measurements and Monte Carlo simulations. The tool is developed and incorporated into 3DSlicer as a plugin. Phantoms are created based on a real patient phantom, Tena, and physiological data for use in radiological protection. Phantoms are developed with only soft, lung, and bone tissue substitutes, represented for the mother and unborn child. This enables the construction of segmented voxel models as well as mesh models (with the ability to export geometries to DICOM format) of the anatomical structures of pregnant women. Additionally, it allows real patient image registration to enable better personalization of the phantom. The tool can help decrease uncertainty in fetal dose estimation, as well as simplify and accelerate the process of fetal dose estimation. It is released publicly to enable further research.

Keywords: diagnostic radiology; radiotherapy; fetal dosimetry personalization; anthropomorphic phantoms creation

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1. Introduction

Pregnant patients undergo diagnostic and therapeutic radiological procedures that expose the unborn child to increased risk due to the use of ionizing radiation [1,2]. The incidence of carcinoma during pregnancy is reported to be 1:1000–1:1500 pregnancies, and according to the FIGO 2018 report, it has increased over the last 30 years [3,4]. Some of these patients will have to undergo radiotherapy (RT) procedures [5]. On the other side, trauma [2,6,7] is the most frequent reason for diagnostic imaging of pregnant patients and occurs in up to 7% of pregnancies [8]. Lack of knowledge and patients' fear can lead to

the unnecessary termination of a pregnancy due to radiation exposure [1,7,8]. In diagnostic and interventional radiology (DIR) and radiotherapy procedures on pregnant patients, the fetal dose must be estimated and optimized. However, the lack of harmonization in clinical practice leads to large differences in fetal dose estimation [2]. For this reason, the SONORA (towards Safe, Optimized and persoNalized radiOlogy and RAdiotherapy procedures for pregnant patients, <https://pianoforte-partnership.eu/sonora/>, accessed on 30 April 2026.) project research focuses on improving the accuracy of fetal dose estimation in DIR and RT to optimize the process and improve benefit/risk communication with the patient. One of the objectives of the project is the development of phantoms at different pregnancy stages with varying patient anatomies to further personalize fetal dose estimation using measurements and Monte Carlo (MC) simulations. These phantoms should reflect different sizes and patient anatomies as well as fetal growth, which causes a series of changes in the mother during the entire period of gestation.

Several voxelized and 3D-printed anthropomorphic phantoms of pregnant women are available for dosimetric research [9,10]. There are libraries of computational phantoms of pregnant patients for use in MC simulations [11]. MC simulations are often used in medical physics as they can provide data beyond experimental techniques, such as dose distributions, organ doses, and spectra information [12]. However, their implementation can be challenging, and additional attention should be introduced when setting them up [13]. Building phantoms while maintaining their anatomical limitations is a complex and time-consuming process, and in the majority of cases, existing models do not represent real patients. For this reason, a tool for building computational phantoms with different anatomical characteristics would benefit the further personalization of fetal dose estimation using MC simulations. Additionally, if the tool can provide files that enable the construction of physical phantoms, it could benefit manufacturing physical phantoms and the experimental estimation of fetal doses. Although there are tools available for phantom modification, none of them are pregnancy specific. Tools such as Slicer RT [14], Plastimatch [15], and Slicer morph [16] offer the possibility of scaling the phantom but have limited capability to provide input for MC simulations (with the exception of Plastimatch) and exporting DICOM files. Within the SONORA activities, such a tool is developed and incorporated in 3D Slicer [17] as a plugin. It enables the building of segmented voxel models as well as mesh models (with the ability to export geometries to DICOM format) of anatomical structures of pregnant women for use in the estimation of fetal doses in diagnostic and interventional radiology and radiotherapy procedures. Phantoms are developed based on a real patient phantom, Tena, produced earlier [9,10] and basic anatomical and physiological data for use in radiological protection [18]. Phantoms are developed with only soft, lung, and bone tissue substitutes represented for both the mother and fetus.

This paper describes a software tool for developing segmented voxel models, mesh (STL) models, and DICOM files of anatomical structures of a pregnant woman for use in the estimation of fetal doses in diagnostic and interventional radiology and radiotherapy procedures.

2. Materials and Methods

2.1. Reference Phantoms Creation

The tool for building personalized voxelized phantoms of pregnant patients, named Fantom Wizard, was based on the pregnant female computational phantom Tena [9,10]. This phantom represents a woman of Central European origin, aged 37, in the 18th week of pregnancy and was based on imaging material from a real patient (MRI of the chest, abdomen, and pelvis during pregnancy and CT scan of the neck, chest, abdomen, and pelvis after childbirth). To enable the use of the phantom in various dosimetric studies, both arms were removed. As the bone marrow in the proximal portions of the humerus

and femur belongs to hematopoietic tissues in adults, both femurs up to the neck were retained as part of the phantom skeleton.

The estimated fetal mass was calculated as the product of the segmented fetal volume (123.04 cm^3) and the average soft tissue density (1.05 g/cm^3 , according to ICRP 89 publication), amounting to 129.2 g. Creating a series of anthropomorphic phantoms of a pregnant woman required modeling phantoms of the 1st trimester (8th week) and 3rd trimester (34th week), which included calculating the expected volume of individual organs and tissues as part of physiological changes in pregnancy. The increase in mass is due to the growth of the pregnant woman's body and the fetus. The average increase shows variable results, although the average increase in mass for first-time mothers is estimated at 12.5 kg [18].

The reference Tena phantom in the 18th gestation week was then transformed to reflect changes due to fetal growth [18] and reference phantoms for the 8th and 34th gestation weeks were developed, first as computational (voxelized, mesh, DICOM) and then as physical phantoms, molded in the same way as the reference Tena phantom [9]. A generalized curve of mass gain during pregnancy was used [18]. Additionally, during the development of the pregnant women and the fetal body, there are changes in maternal body composition. Generally, the body in pregnancy can be seen as two subunits connected into a whole: the fetus, which includes the embryo/fetus, amniotic fluid, placenta, and uterus; and the mother, where the structures that change most during pregnancy are the breasts, adipose tissue, blood volume, and extracellular fluids. For proper modeling of phantoms of pregnant women in different gestational periods or trimesters, it is necessary to know the expected physiological processes that occur during pregnancy with individual organs. These processes are often difficult to predict due to their complexity and the multitude of influencing factors. In the growth and development of the human body, individual differences mean that growth and development curves are not identical for each person and are a consequence of age, gender, racial, and other factors. The International Commission on Radiation Protection (ICRP), in its 89th publication edition, systematized the growth and development curves of the human body, from conception to pregnancy, based on available research, and this was used in developing Tena phantoms in 8th and 34th gestation weeks [18].

2.1.1. Changes in Fetus (Fetus, Amniotic Fluid, Placenta, and Uterus)

Research on prenatal development was performed based on anthropometric measurements at different gestational ages, and the results are usually presented as a longitudinal view of growth. Nevertheless, even under ideal circumstances (younger maternal age with a median age of 28 years, uretic body mass, optimal calorie intake, absence of socioeconomic difficulties), there are very large variations. For example, at the 37th week of gestation, the physiological mass of the fetus ranges from 2205 g to 2538 g [19]. The placenta grows in two phases: linearly until the 24th week (when its mass is about 150 g), after which the increase in mass becomes more pronounced. During childbirth, the placenta mass averages 600–700 g, with variations ranging from 500 to 1000 g [20]. The mass of amniotic fluid in the first half of pregnancy correlates with fetal mass. In the second half of pregnancy, estimating the volume of amniotic fluid is difficult, and extremely variable values are obtained—according to research, the volume can range from 500 to 3000 mL, and by term it further decreases. Correlations have been found between amniotic fluid volume and the body mass index, gestational age, estimated fetal mass, and abdominal circumference of the pregnant woman [21]. The estimated mean mass of non-pregnant uteruses ranges from 50 g to 100 g in multiparous women (<5 pregnancies). During pregnancy, it expands many times (up to 1000 times, from 10 mL of intrauterine volume to 5000 mL), while volume and mass increase linearly, and can weigh up to 1100 g at the time of delivery [18].

2.1.2. Changes in the Mother's Body (Breasts, Adipose Tissue, Blood, and Extracellular Fluids)

The increase in adipose tissue mass is one of the most variable components of the total mass gain in a pregnant woman. To date, limited research has been conducted on body composition analysis during pregnancy, so available data are scarce. These indicate a linear increase of up to about 2 kg per trimester (or slightly less), or a total increase in body fat volume of approximately 5.45 ± 4.72 L during pregnancy. The increase in adipose tissue mass depends on several factors, including the pre-pregnancy body mass index, the sex of the fetus, and the number of pregnancies [22]. During pregnancy, the compartments in which adipose tissue preferentially accumulate (visceral-subcutaneous, upper-lower body, subscapular, thighs) also depend on these factors. A challenge in phantom modeling determines the distribution of adipose tissue, particularly regarding changes in breast volume. According to the ICRP, the average breast volume of first-time mothers in early pregnancy is about 565 mL, increasing to an average of 775 mL at term. The increase in breast volume follows a linear trend, with an average increase of 96 mL regardless of initial breast volume [23]. In summary, numerous organs and tissues undergo various physiological changes during pregnancy, depending on both predictable and unpredictable factors, and follow different volumetric curves, with a distinct emphasis on individual differences. Additionally, body fluid volumes change during pregnancy. To simplify phantom modelling and given the extreme variability of fluid volume during pregnancy, changes in blood volume and extracellular fluids were omitted, although it is known that about 2 L of blood and 2 L of extracellular fluids accumulate during pregnancy [24]. Similarly, changes in bone mass were not considered in the modeling of the phantom series, as they are insufficiently researched, and likely refer to extremely small, negligible masses [25].

2.2. Software Tool for Creating Personalized Phantoms of Pregnant Patients

Since differences in height, mass, maternal circumference, and breast size influence fetal dose in DIR and in RT procedures, it was decided to further personalize these phantoms by adjusting these parameters. For this reason, the 3DSlicer [17] plugin was developed with the capability to modify these parameters.

Human height is mainly determined by the growth of the long-shaft bones of the legs, while the spinal column contributes to the height on a smaller scale. Studies have shown that height influences the mass of internal organs only in males, while the mass of the body positively correlates to the mass of the organs in both the females and males [26]. As the Tena phantom lacks extremities, for easier 3D modelling and subsequent software development, it was decided that each vertebral body would be slightly increased or decreased in height to gain or lose the overall body height. For simplicity, internal organs were modeled to remain unchanged in size, while soft tissue volume was increased. To ensure better alignment with the real patient being modelled, the generated computational phantom can be additionally combined with real patient CT images. Additionally, for phantoms in the third gestation period, fetal orientation can be changed.

A description of the reference phantom development within the tool is provided in the Supplementary Materials.

The final tool was developed as a plugin for 3DSlicer using Python (version 3.9.10). The user is prompted to enter the desired trimester and fetal orientation (in the case of the second trimester), as well as the desired phantom mass and height. The valid ranges for mass and height are queried from the appropriate lookup table. A description of the tool development is provided in the Supplementary Materials.

3. Results

3.1. Organ Volumes and Masses Calculation for Reference Phantoms

To calculate the volume required for modelling the computational phantom of a pregnant woman, data on the expected mass of specific organs or tissues that change during pregnancy, as well as tissue density, were used. The female subject (hereafter referred to as “Tena”) had a body mass of 60 kg before pregnancy. According to available medical documentation from an examination in the 18th week of pregnancy, the mass was 72 kg. Therefore, the increase in body mass in the 18th week was 12 kg. For phantom modeling, it is necessary to determine the volumes of specific tissues of interest for a given gestational age: adipose tissue volume (i.e., the increase in adipose tissue volume, as the existing adipose tissue volume from the previous phantom is added to each subsequent trimester), uterine volume, and fetal volume. Since the reference Tena phantom had a mass of 49.7 kg in the 18th week of pregnancy, the mass of the body and head before pregnancy was calculated as follows:

$$m_{\text{body}} = m_{\text{arms+legs}} + m_{\text{torso+head}}$$

$$m_{\text{arms+legs}} = m_{\text{body}} - m_{\text{torso+head}}$$

$$m_{\text{arms+legs}} = 72 \text{ kg} - 49.7 \text{ kg}$$

$$m_{\text{arms+legs}} = 22.3 \text{ kg}$$

It follows from the above that

$$m_{\text{torso+head before pregnancy}} = m_{\text{body before pregnancy}} - m_{\text{arms+legs}}$$

$$m_{\text{torso+head before pregnancy}} = 60 \text{ kg} - 22.3 \text{ kg} = 37.7 \text{ kg}$$

According to the ICRP (the closest data are for the 20th week of pregnancy)

$$m_{\text{fetal unit}} = m_{\text{fetus}} + m_{\text{placenta}} + m_{\text{amniotic fluid}} + m_{\text{uterus}}$$

$$m_{\text{fetal unit}} = 300 \text{ g} + 170 \text{ g} + 350 \text{ g} + 320 \text{ g} = 1140 \text{ g} = 1.140 \text{ kg}$$

$$m_{\text{whole body in the 18th week of pregnancy}} = m_{\text{torso+head before pregnancy}} + m_{\text{fetal unit}} + m_{\text{increase in adipose tissue}};$$

$$m_{\text{increase in adipose tissue}} = m_{\text{whole body in the 18th week of pregnancy}} - m_{\text{torso+head before pregnancy}} - m_{\text{fetal unit}}$$

$$m_{\text{increase in adipose tissue}} = 49.7 \text{ kg} - 37.7 \text{ kg} + 1.14 \text{ kg} = 10.86 \text{ kg} = 10\,860 \text{ g}.$$

It follows that the volume of adipose tissue growth in the 18th week of pregnancy compared to before pregnancy is

$$\begin{aligned} \text{Increase in adipose tissue} &= \text{increase in adipose tissue mass divided by density of adipose tissue} = 10.86 \\ &\text{kg divided by } 900 \text{ kg per m}^3 = 0.01207 \text{ m}^3 = 12070 \text{ mL}. \end{aligned}$$

In ICRP Publication 89, data on the fetal mass, amniotic fluid, placenta, and uterus for 30 and 38 weeks of gestational age are available, and given that the phantom of interest is modeled for the corresponding 34th week of pregnancy, organ mass was calculated as an arithmetic mean.

The mass *of the fetus* is 1500 g in the 30th week and 3400 g in the 38th week. Accordingly, the approximate mass of the fetus at 34 weeks is 2450 g.

The mass *of amniotic fluid* at 30 weeks is 750 g, and at 38 weeks, it is 800 g. Accordingly, the mass of amniotic fluid at week 34 is 775 g.

The mass *of the placenta* at week 30 is 430 g, and at week 38, it is 650 g. Therefore, the approximated mass of the placenta at week 34 is 540 g.

The mass *of the uterus* in the 30th week is 600 g, and the mass of the uterus in the 38th week is 970 g. Accordingly, the approximated mass of the uterus at week 34 is 785 g.

In the 34th week of pregnancy, an increase in body mass of 20 kg was recorded at the follow-up medical examination.

$$\text{increase } m_{\text{total}} = \text{increase } m_{\text{adipose tissue}} + m_{\text{fetal unit}}$$

Therefore,

$$\text{increase } m_{\text{adipose tissue}} = \text{increase } m_{\text{total}} - m_{\text{fetal unit}}$$

$$\text{increase } m_{\text{adipose tissue}} = 15.45 \text{ kg}$$

It follows,

Volume increase of adipose tissue = mass increase divided by density of adipose tissue = 15.45 kg divided by 900 kg per m³ = 17166.7 cm³ = 17 166.7 mL.

According to the above calculation, three reference computational Tena phantoms are created (Figure 1) and physical phantoms are also molded.

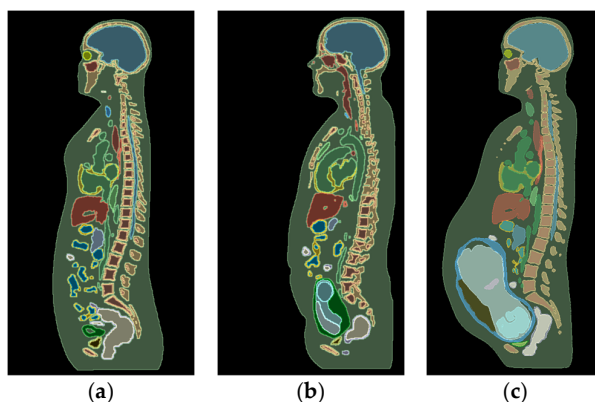


Figure 1. Reference phantoms: (a) first, (b) second, and (c) third trimester.

3.2. Software Tool and Workflow

Software tool (Fantom Wizard)—3DSlicer plugin, for the development of personalized computational phantoms of pregnant patients for computational dosimetry applications, is available as an open-source repository on GitHub (<https://github.com/lsmic/FantomWizard> (accessed on 30 April 2026)). The tool description and installation instructions are available as a part of the repository. Instructions describe input parameters for phantom building different possibilities of voxel sizes, exporting different formats of phantoms. User interface and workflow showing how to build and register the phantom from beginning to end are given in Figures 2–7.

To set up the CreateFantomModule in 3D Slicer, begin by cloning the repository to your local machine. Once the repository has been downloaded, open the 3D Slicer application. From the top menu, navigate to Edit, select Application Settings, and go to the Modules section. In this area, you will find a field labeled Additional module paths. Drag and drop the CreateFantomModule folder into this field to add it as an external module. After completing these steps, the module will be available for use within 3D Slicer.

The user interface is built to be as user friendly as possible (Figure 2), and it can be found in Slicer Modules under Wizards—Create Fantom. After selecting the module, the Fantom Wizard opens in the module panel. The Fantom Wizard is divided into three main tabs (Figure 2):

- **Generate**—Build a personalized phantom by specifying patient parameters (trimester, height, mass), resolution (voxel size), and required organs.
- **Blend**—Extend CT imaging by blending its segmentation with the phantom generated in the Generate tab.
- **Export**—Used for exporting the created phantoms in DICOM and voxelized format.

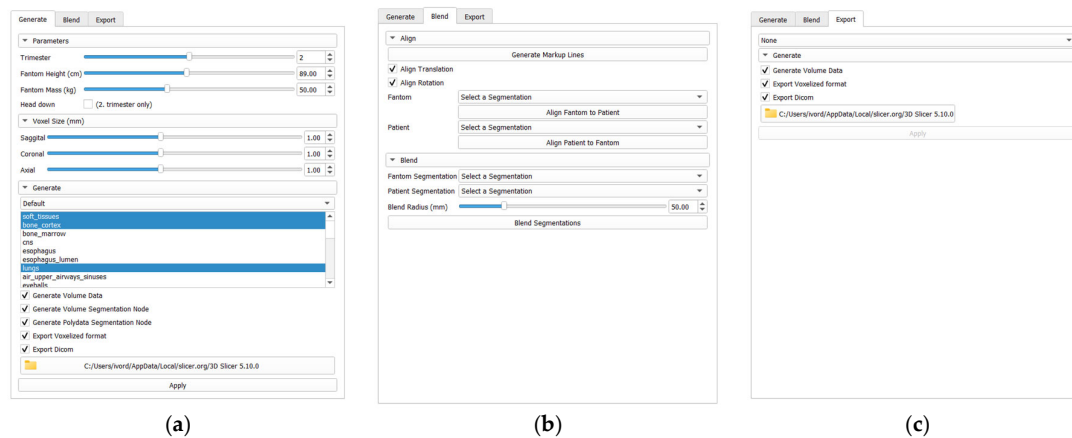


Figure 2. Phantom Wizard user interface with three tabs: (a) Generate, (b) Blend, and (c) Export.

The full capabilities of the Phantom Wizard can be seen in the workflow for creating a blended model, which includes the following steps (Figures 3–7):

1. **Patient segmentation:** Segmentation is created in 3D Slicer using partial patient CT imaging data (Figure 3).
2. **Phantom generation:** The parameters for building the personalized phantom are defined (Figure 4) (gestational trimester, fetal orientation phantom height from the bottom of the torso excluding legs and mass excluding arms and legs). The phantom is then built with the possibility to further adjust the parameters to better match the real patient. The generated phantom can be exported as a standalone model and does not require blending with patient CT segmentations.
3. **Reference point placement:** Reference point placement: Markup lines need to be positioned in the same places in the generated phantom and patient CT (Figure 5).
4. **Alignment of phantom and patient:** Prior to alignment, imported CT data of the patient must be named in the same manner as the segments in the generated phantom. The structures are then aligned (Figure 6), and the procedure can be repeated iteratively to improve the fit.
5. **Blending of phantom and patient:** In the end, both structures are blended, and the volume of the final phantom is generated (Figure 7).

After creating the phantom, it can be exported in DICOM, mesh, and voxelized form to be used for computational purposes or for the production of physical representation. Usually for RT, supradiaphragmatic CT images are used as the patient data, with the rest of the patient developed according to the above-described method. For DIR procedures, abdominal CT images could also be acquired and used for computational phantom development.

The generation of a personalized computational phantom (Figures 3–7) can last for several minutes using an average desktop computer, mainly depending on the desired voxel size. The time for creating a computational phantom by adjusting it to the real patient CT (Figure 4) highly depends on user skills and experience.

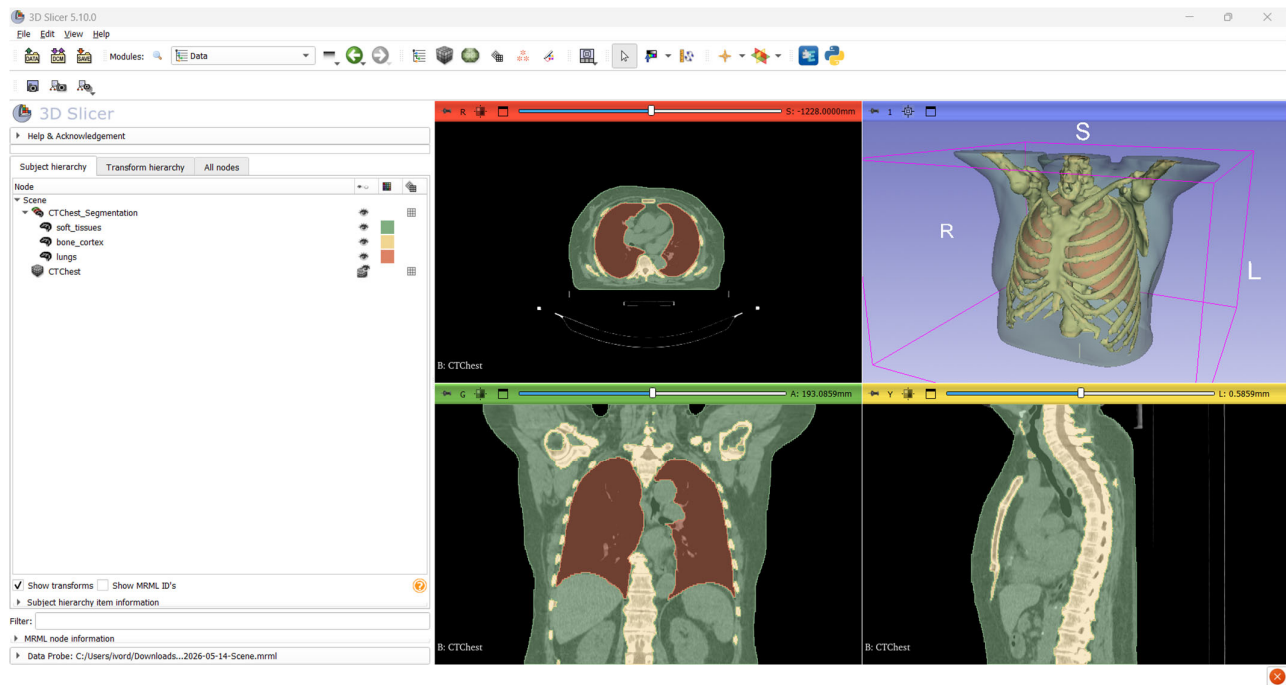


Figure 3. Segmentation created from CT imaging data.

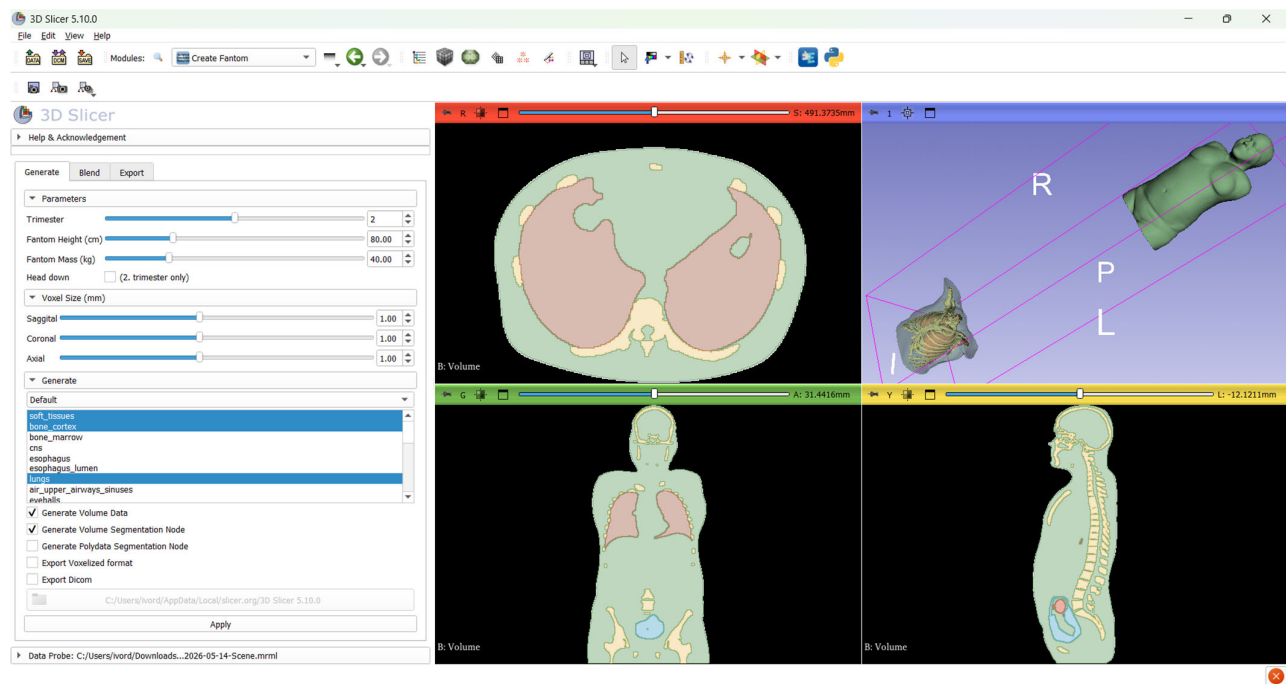


Figure 4. Phantom developed by the tool (Fantom Wizard).

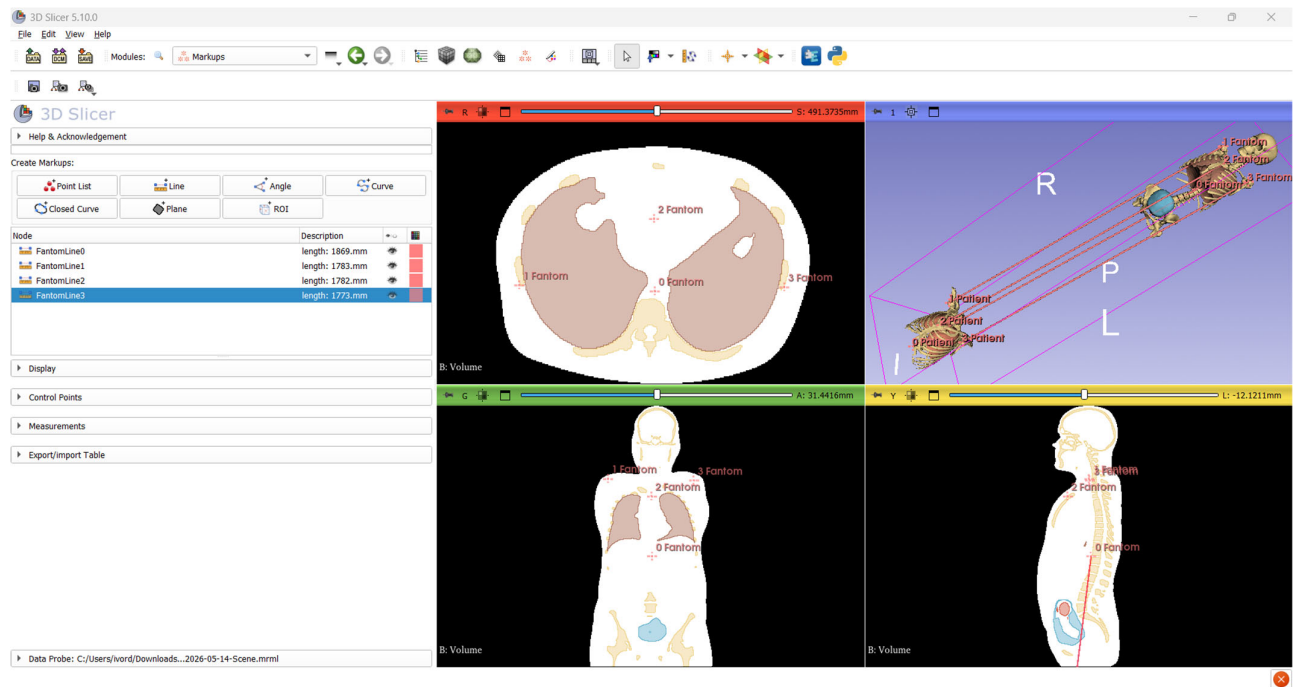


Figure 5. Generating and placing markup lines.

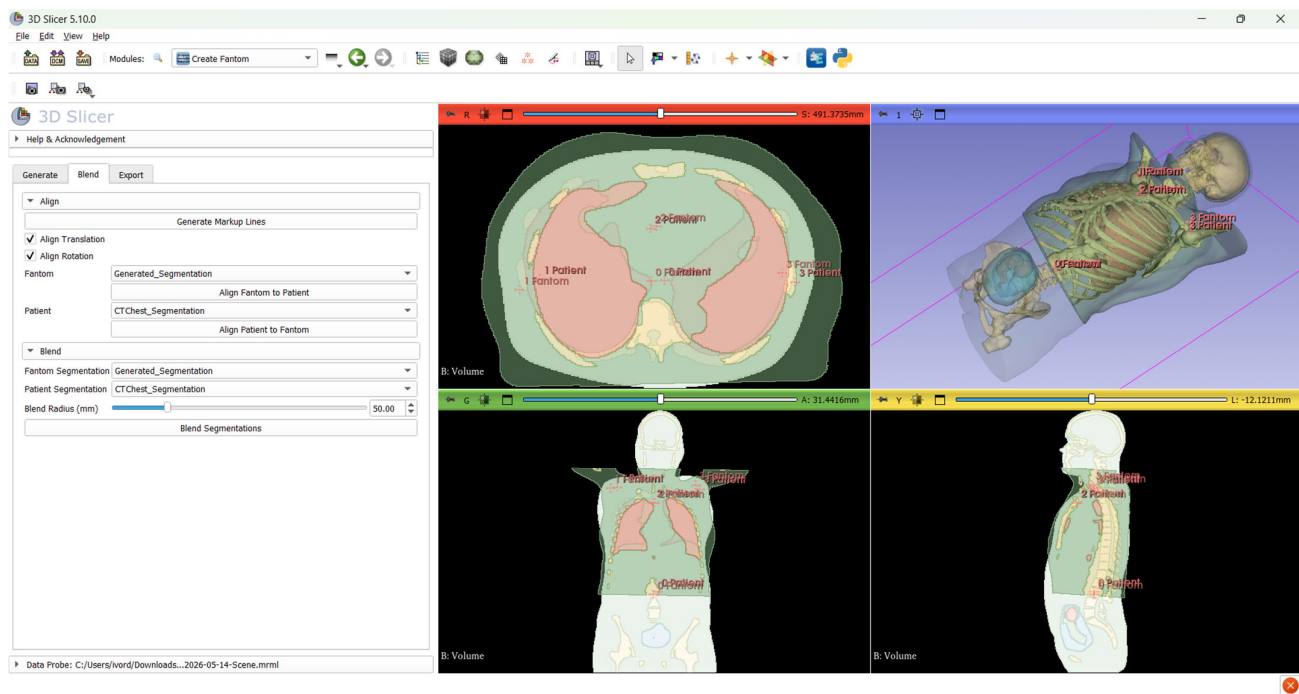


Figure 6. Aligned segmentations of CT imaging data and phantom developed by the tool.

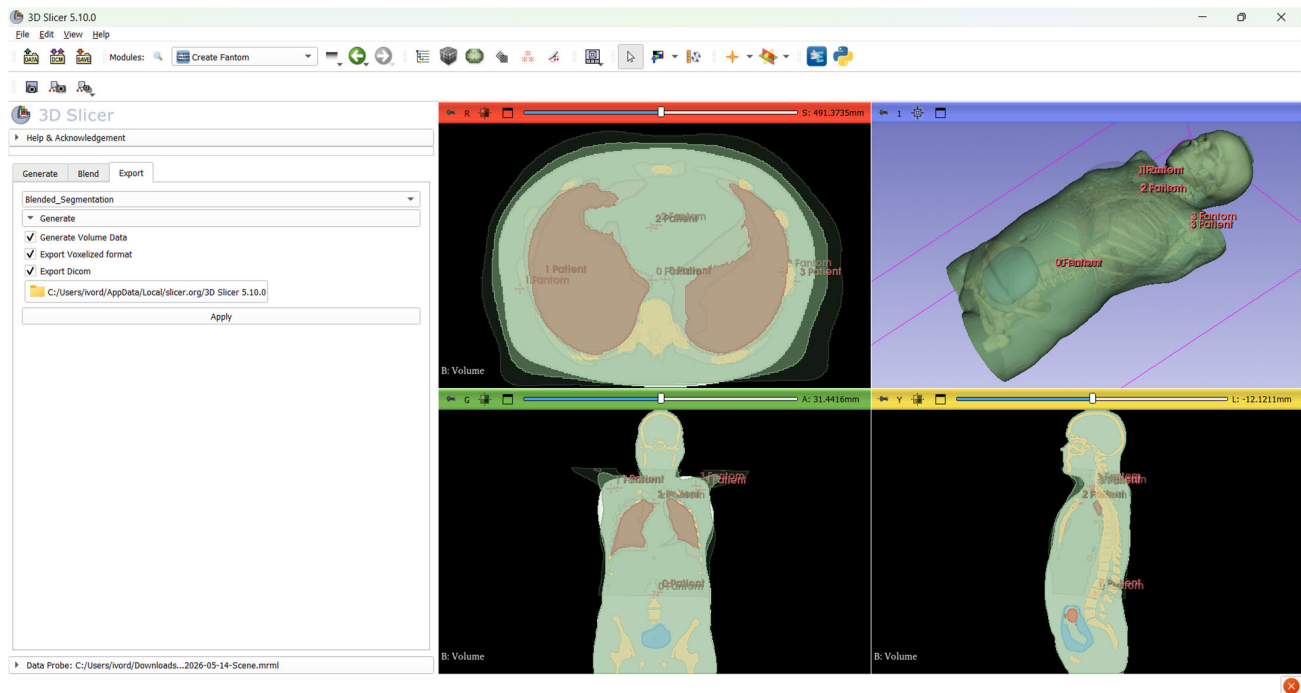


Figure 7. Blended model developed by the tool.

3.3. Clinical Applications

To demonstrate the power and flexibility of Fantom Wizard, example phantoms that can be created are presented (Figure 8a–c). The phantoms present the Tena phantom in gestation period 2 with a height difference of 10 cm and the same body mass (Figure 8a,b) and the Tena phantom in gestation period 3 with the same height as the phantom presented in Figure 8c. The DICOM, mesh, and voxelized form files of each phantom are provided in the Supplementary Materials.

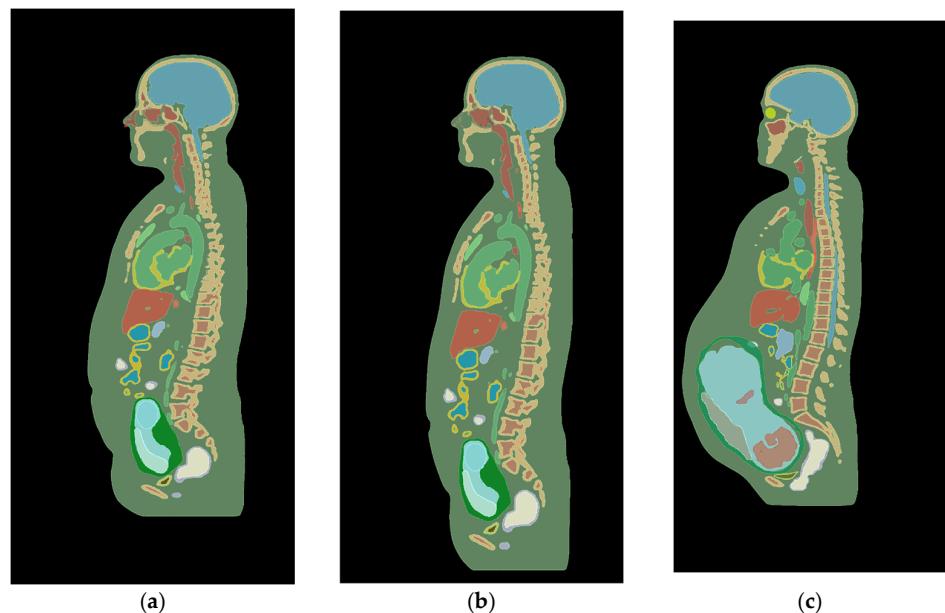


Figure 8. The phantoms generated by the tool: (a) Tena 2 mass 51 height 84, (b) Tena 2 mass 51 height 94, and (c) Tena 3 mass 51 height 84.

The examples have been chosen to show possible differences in patient anatomies that could influence fetal doses in RT and DIR. Since fetal dose highly dependent on the distance of the fetus from the beam edge in RT as well as in DIR procedures, there will be significant fetal dose difference for radiological breast procedures for patients presented in Figure 8a,b, e.g., using conformal 6 MV photon beams for RT of the breast, in the lower patient (Figure 8b), the fetal dose could be doubled compared to the patient presented in Figure 8a. This value strongly depends on the radiation field edge distance from the fetus and was estimated according to the fetal dose estimation guidelines given by AAPM [27]. Although this is a rough estimate, it shows the need for pregnant phantom personalization. Similarly, in diagnostic and interventional radiology procedures on pregnant patients when the fetus is in the primary beam, the fetal dose strongly depends on the patient abdominal size [28], and the patient presented in Figure 8c would have a significantly higher fetal dose or lower image quality.

3.4. Evaluation

The quantitative evaluation of geometrical accuracy is provided in Table 1, where organ volumes data, generated for phantoms in all first two trimesters, are compared with ICRP reference phantoms [29,30]. ICRP offers phantoms at gestational ages of 10 and 17 weeks, which is closest to Tena 1 (8 weeks) and Tena 2 (17 weeks). The generated phantoms were adjusted to fit ICRP phantoms with their mass and height, namely, Tena phantoms were generated as 84 cm high without legs and body masses of 35 and 37 kg, respectively.

Table 1. Comparison of ICRP phantoms and those developed with our tool. The volume of the organs is given as well as the overall volume of the phantom. For Tena 1, the phantom height was 84 cm and the body mass was 37 kg. Tena 2 was 84 cm high and had a mass of 37 kg. For the ICRP phantom, data for arms and legs were not calculated.

	Volume [cm ³]			
	ICRP 10 Weeks	ICRP 17 Weeks	Tena 1	Tena 2
Soft tissue	22,022.1	22,639.0	22,670.6	23,241.6
Bones	2352.9	2360.0	2290.0	2281.4
Bone marrow	1762.3	1771.9	670.8	668.2
Nerves	1244.6	1247.2	1153.9	1154.0
Esophagus	41.2	41.7	11.0	11.0
Esophagus lumen	20.2	20.2	4.1	4.0
Lungs	2209.3	2260.6	3648.8	3626.5
Air in body	27.4	27.3	133.7	133.3
Eyeballs	14.6	14.6	12.4	12.4
Eyeballs	68.2	68.0	29.4	29.4
Myocardium	277.7	280.2	201.6	200.6
Colon	429.9	435.3	214.1	264.2
Colon content	304.8	304.8	595.4	418.0
Stomach, small intestine	886.9	898.1	371.0	387.9
Stomach, small intestine contents	485.7	485.7	810.1	523.4
Liver	1729.8	1753.1	1652.0	1641.7
Spleen	179.3	182.7	363.0	360.8
Kidneys	341.5	350.5	289.4	287.5
Gallbladder	7.8	7.8	14.5	14.4
Gallbladder content	45.7	45.7	15.2	15.2
Pancreas	138.6	140.1	79.0	78.5
Adrenal glands	14.8	14.9	4.7	4.7

Blood	707.4	750.6	744.6	739.6
Thyroid	18.6	18.7	10.0	9.2
Uterus	236.9	592.4	38.3	965.1
Urinary bladder	53.5	53.5	20.2	19.7
Urinary bladder content	190.5	190.5	13.0	10.3
Overall volume	35812.3	36955.1	36060.7	37102.4

In the ICRP phantoms, volumes of extremities were not calculated, while the “common denominator” for the fetus, amniotic fluid, and placenta in both phantoms is the uterus. Since the Tena 1 phantom is two weeks younger in gestational age, it is reasonable that the uterus volume is lower. It should be also taken into consideration that the Tena phantom is based on a real patient scenario.

4. Discussion

Within this study, software enabling the creation of personalized pregnant female phantoms has been developed and named Fantom Wizard. It is available as open-source software (under an MIT license) and can be used by the scientific community to improve fetal dosimetry in DIR and RT procedures performed on pregnant patients. Although similar tools exist (SlicerRT, Slicermorph, and Platimatch), none of them are dedicated to pregnant patients and have the possibility to export in several computational formats simultaneously. Fantom Wizard allows for building personalized pregnant patients as computational phantoms for MC simulations as well as providing geometry for building physical phantoms for fetal dose measurements (Figure 3). A Tena anthropomorphic phantom of a pregnant female was used as a reference [9,10]. The ICRP is also developing pregnant female Mesh-type reference computational phantoms [29,30]. Nevertheless, Fantom Wizard goes beyond reference phantom creation. This approach can be used to build similar tools for the personalization of phantoms with ICRP reference phantoms. Even then, this tool can add value for the further personalization of pregnant patient dosimetry (experimental or using MC simulations).

The main limitation of Fantom Wizard is that phantoms development is based on ICRP reference organ data [18], though large variations among pregnant women exist. The same applies to variations in heights and masses of patients. When comparing ICRP phantoms [29,30] with phantoms of similar gestation age, height, and mass generated by Fantom Wizard, there are significant differences between some of the organs (Table 1). This limitation here is addressed with the possibility of registering the real patient CT and then adjusting it within the tool (Figure 7). An additional limitation that influences the fetal dose estimation is variations in fetus positions. At this stage, this is addressed only as a possibility to change the fetal orientation in the second gestational period. Nevertheless, this can be further investigated in terms of involving the dosimetric impact of anatomical variations of pregnant patients undergoing DIR or RT procedures.

There are several fetal dose estimation methods and tools in DIR, but it has been shown that the uncertainties of these methods are not well known in clinical routine [2]. In RT, fetal dose estimation methods mostly rely on approximations developed from the distance between the edge of the radiation field and the fetus [31]. Fantom Wizard offers the possibility of developing a computational anthropomorphic phantom of a pregnant woman for use in MC simulations and fetal dose estimation. The tool can provide DICOM files of the patient that can be used for dosimetric studies in RT or even used in treatment planning systems. Additionally, there is the possibility of exporting mesh format files, which enables 3D printing of the same phantom and performing experiments on identical geometry as MC simulations. This can influence current dosimetry practices in clinics, enabling better understanding of fetal dose estimation methods used routinely.

The example phantoms (Figure 8a–c) are developed by the software tool to show the need for pregnant phantom personalization. Fetal doses for different RT or DIR procedures could differ significantly in these example phantoms. Also, AAPM 36 and 158 [27,31] emphasize that the determination of fetal doses during radiotherapy should be improved by performing MC simulations and measurements in dedicated anthropomorphic phantoms.

As demonstrated in Table 1, Fantom Wizard successfully created phantoms matching those provided by ICRP, perfectly matching overall phantom volume. The discrepancies might occur since Tena Phantom is based on the real case scenario of the pregnant female.

Fantom Wizard has been developed to enable the more personalized estimation of fetal dose in DIR and RT procedures. This should help decrease fetal dose estimation uncertainty as well as simplify and speed up the process of fetal dose estimation. It is released publicly to enable further research.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16115404/s1>.

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References

- De Saint-Hubert, M.; Tyminińska, K.; Stolarczyk, L.; Brkić, H. Fetus Dose Calculation during Proton Therapy of Pregnant Phantoms Using MCNPX and MCNP6. 2 Codes. *Radiat. Meas.* **2021**, *149*, 106665. <https://doi.org/10.1016/J.RADMEAS.2021.106665>.
- Faj, D.; Bassinet, C.; Brkić, H.; De Monte, F.; Dreuil, S.; Dupont, L.; Ferrari, P.; Gallagher, A.; Gallo, L.; Huet, C.; et al. Management of Pregnant or Potentially Pregnant Patients Undergoing Diagnostic and Interventional Radiology Procedures: Investigation of Clinical Routine Practice. *Phys. Medica* **2023**, *115*, 103159. <https://doi.org/10.1016/J.EJMP.2023.103159>.
- Basta, P.; Bak, A.; Roszkowski, K. Cancer Treatment in Pregnant Women. *Contemp. Oncol.* **2015**, *19*, 354.
- Botha, M.H.; Rajaram, S.; Karunaratne, K. Cancer in Pregnancy. *Int. J. Gynecol. Obstet.* **2018**, *143*, 137–142.
- Geng, C.; Moteabbed, M.; Seco, J.; Gao, Y.; Xu, X.G.; Ramos-Méndez, J.; Faddegon, B.; Paganetti, H. Dose Assessment for the Fetus Considering Scattered and Secondary Radiation from Photon and Proton Therapy When Treating a Brain Tumor of the Mother. *Phys. Med. Biol.* **2015**, *61*, 683.
- ICRP. *Annals of the ICRP. Publication 84. Pregnancy and Medical Radiation*; Pergamon Press: Oxford, UK, 2000. Available online: https://journals.sagepub.com/doi/pdf/10.1177/ANIB_30_1 (accessed on 15 May 2026).

7. Tomić, A.; Brkić, H.; Turk, T.; Kasabašić, M.; Bjelobrk, I.; Kralik, I.; De Monte, F.; Zancopè, N.; Lombardi, R.; Majer, M.; et al. Fetal Radiation Dose in Common Diagnostic Radiology Procedures for Pregnant Patients: Findings from In-Phantom Measurements. *Appl. Sci.* **2025**, *15*, 1143. <https://doi.org/10.3390/app15031143>.
8. Raptis, C.A.; Mellnick, V.M.; Kitchin, D.; Radiologists, M.; Fowler, K.J. Imaging of Trauma in the Pregnant Patient. *Radio Graph.* **2016**, *34*, 748–763. <https://doi.org/10.1148/rg.343135090>.
9. Kopačin, V.; Brkić, H.; Ivković, A.; Kasabašić, M.; Knežević, Ž.; Majer, M.; Nodilo, M.; Turk, T.; Faj, D. Development and Validation of the Low-Cost Pregnant Female Physical Phantom for Fetal Dosimetry in MV Photon Radiotherapy. *J. Appl. Clin. Med. Phys.* **2024**, *25*, e14240. <https://doi.org/10.1002/ACM2.14240>.
10. Kopacin, V.; Kasabasic, M.; Faj, D.; de Saint Hubert, M.; Galic, S.; Ivkovic, A.; Majer, M.; Brkic, H. Development of a Computational Pregnant Female Phantom and Calculation of Fetal Dose during a Photon Breast Radiotherapy. *Radiol. Oncol.* **2022**, *56*, 541–551. <https://doi.org/10.2478/RAON-2022-0039>.
11. Maynard, M.R.; Long, N.S.; Moawad, N.S.; Shifrin, R.Y.; Geyer, A.M.; Fong, G.; Bolch, W.E. The UF Family of Hybrid Phantoms of the Pregnant Female for Computational Radiation Dosimetry. *Phys. Med. Biol.* **2014**, *59*, 4325–4343. <https://doi.org/10.1088/0031-9155/59/15/4325>.
12. Huet, C.; Eakins, J.; Zankl, M.; Gómez-Ros, J.M.; Jansen, J.; Moraleda, M.; Struelens, L.; Akar, D.K.; Borbinha, J.; Brkić, H.; et al. Monte Carlo Calculation of Organ and Effective Doses Due to Photon and Neutron Point Sources and Typical X-Ray Examinations: Results of an International Intercomparison Exercise. *Radiat. Meas.* **2022**, *150*, 106695. <https://doi.org/10.1016/J.RADMEAS.2021.106695>.
13. Rabus, H.; Gomez-Ros, J.-M.; Villagrasa, C.; Eakins, J.; Vrba, T.; Blideanu, V.; Zankl, M.; Tanner, R.; Struelens, L.; Brkić, H. Quality Assurance for the Use of Computational Methods in Dosimetry: Activities of EURADOS Working Group 6 ‘Computational Dosimetry’. *J. Radiol. Prot.* **2021**, *41*, 46.
14. Pinter, C.; Lasso, A.; Wang, A.; Jaffray, D.; Fichtinger, G. SlicerRT: Radiation Therapy Research Toolkit for 3D Slicer. *Med. Phys.* **2012**, *39*, 6332–6338. <https://doi.org/10.1118/1.4754659>.
15. Zaffino, P.; Raudaschl, P.; Fritscher, K.; Sharp, G.C.; Spadea, M.F. Technical Note: Plastimatch Mabs, an Open Source Tool for Automatic Image Segmentation. *Med. Phys.* **2016**, *43*, 5155–5160. <https://doi.org/10.1118/1.4961121>.
16. Rolfe, S.; Pieper, S.; Porto, A.; Diamond, K.; Winchester, J.; Shan, S.; Kirveslahti, H.; Boyer, D.; Summers, A.; Maga, A.M. Slicer-Morph: An Open and Extensible Platform to Retrieve, Visualize and Analyze 3D Morphology. *Methods Ecol. Evol.* **2021**, *12*, 1816–1825. <https://doi.org/10.1111/2041-210X.13669>.
17. Kikinis, R.; Pieper, S.D.; Vosburgh, K.G. 3D Slicer: A Platform for Subject-Specific Image Analysis, Visualization, and Clinical Support. In *Intraoperative Imaging and image-Guided Therapy*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 277–289.
18. ICRP. Publication 89. *Basic Anatomical and Physiological Data for Use in Radiological Protection Reference Values*; SAGE Publications Sage UK: London, UK, 2002; Volume 32.
19. Jacobson, M.H.; Wang, Y.; Long, S.E.; Liu, M.; Ghassabian, A.; Kahn, L.G.; Afanasyeva, Y.; Brubaker, S.G.; Mehta-Lee, S.S.; Trasande, L. The Effect of Maternal US Nativity on Racial/Ethnic Differences in Fetal Growth. *Am. J. Epidemiol.* **2022**, *191*, 1568–1583. <https://doi.org/10.1093/AJE/KWAC072>.
20. Sletner, L.; Yajnik, C.S.; Turowski, G.; Michelsen, T.M.; Sommer, C.; Birkeland, K.I.; Roald, B.; Jenum, A.K. Placental Weight, Surface Area, Shape and Thickness—Relations with Maternal Ethnicity and Cardio-Metabolic Factors during Pregnancy. *Placenta* **2024**, *148*, 69–76. <https://doi.org/10.1016/J.PLACENTA.2024.02.002>.
21. Kirshenbaum, M.; Ziv-Baran, T.; Katorza, E. Amniotic Fluid Index Measurements in the Second and Third Trimester and Correlation to Fetal Biometric Parameters—New Reference Based on a Big Retrospective Data. *J. Matern. Fetal. Neonatal Med.* **2022**, *35*, 8176–8180. <https://doi.org/10.1080/14767058.2021.1965981>.
22. Vesco, K.K.; Marshall, N.E.; Baetscher, E.; Leo, M.C.; Rooney, W.; Francisco, M.; Baker, E.; King, J.C.; Catalano, P.; Frias, A.E.; et al. Changes in Visceral and Ectopic Adipose Tissue Stores Across Pregnancy and Their Relationship to Gestational Weight Gain. *J. Nutr.* **2022**, *152*, 1130–1137. <https://doi.org/10.1093/JN/NXAC010>.
23. Bayer, C.M.; Bani, M.R.; Schneider, M.; Dammer, U.; Raabe, E.; Haeberle, L.; Faschingbauer, F.; Schneeberger, S.; Renner, S.P.; Fischer, D.; et al. Assessment of Breast Volume Changes during Human Pregnancy Using a Three-Dimensional Surface Assessment Technique in the Prospective CGATE Study. *Eur. J. Cancer Prev.* **2014**, *23*, 151–157. <https://doi.org/10.1097/CEJ.0B013E3283651CCB>.
24. Most, J.; Marlatt, K.L.; Altazan, A.D.; Redman, L.M. Advances in Assessing Body Composition during Pregnancy. *Eur. J. Clin. Nutr.* **2018**, *72*, 645. <https://doi.org/10.1038/S41430-018-0152-8>.

25. Purdie, D.W.; Aaron, J.E.; Selby, P.L. Bone Histology and Mineral Homeostasis in Human Pregnancy. *Br. J. Obstet. Gynaecol.* **1988**, *95*, 849–854. <https://doi.org/10.1111/J.1471-0528.1988.TB06568.X>.
26. Mubbunu, L.; Bowa, K.; Petrenko, V.; Silitongo, M. Correlation of Internal Organ Weights with Body Weight and Body Height in Normal Adult Zambians: A Case Study of Ndola Teaching Hospital. *Anat. Res. Int.* **2018**, *2018*, 4687538. <https://doi.org/10.1155/2018/4687538>.
27. Stovall, M.; Blackwell, C.R.; Cundiff, J.; Novack, D.H.; Palta, J.R.; Wagner, L.K.; Webster, E.W.; Shalek, R.J. Fetal Dose from Radiotherapy with Photon Beams: Report of AAPM Radiation Therapy Committee Task Group No. 36. *Med. Phys.* **1995**, *22*, 63–82. <https://doi.org/10.1118/1.597525>.
28. Almohammed, H.I.; Elshami, W.; Hamd, Z.Y.; Abuzaid, M. Optimizing CT Abdomen–Pelvis Scan Radiation Dose: Examining the Role of Body Metrics (Waist Circumference, Hip Circumference, Abdominal Fat, and Body Mass Index) in Dose Efficiency. *Tomography* **2024**, *10*, 643–653. <https://doi.org/10.3390/TOMOGRAPHY10050049>.
29. Shin, B.; Kim, S.; Choi, C.; Kim, H.; Yeom, Y.S.; Chung, B.S.; Nguyen, T.T.; Bolch, W.E.; Moon, S.; Han, H.; et al. ICRP Pregnant-Female Mesh-Type Reference Computational Phantoms Part 2: Development of Maternal Phantoms. *Phys. Med. Biol.* **2025**, *70*, 095008. <https://doi.org/10.1088/1361-6560/add07a>.
30. Shin, B.; Kim, S.; Choi, C.; Kim, H.; Yeom, Y.S.; Chung, B.S.; Nguyen, T.T.; Moon, S.; Bolch, W.E.; Kim, C.H. ICRP Pregnant-Female Mesh-Type Reference Computational Phantoms Part 1: Development of Fetal Phantoms. *Phys. Med. Biol.* **2024**, *69*, 245015. <https://doi.org/10.1088/1361-6560/ad9a35>.
31. Kry, S.F.; Bednarz, B.; Howell, R.M.; Dauer, L.; Followill, D.; Klein, E.; Paganetti, H.; Wang, B.; Wu, C.-S.; George Xu, X. AAPM TG 158: Measurement and Calculation of Doses Outside the Treated Volume from External-Beam Radiation Therapy. *Med. Phys.* **2017**, *44*, e391–e429. <https://doi.org/10.1002/mp.12462>.

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