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Hybrid computational pregnant female phantom construction for radiation dosimetry applications

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Abstract

The number of patients undergoing diagnostic radiology and radiation therapy procedures has increased drastically owing to improvements in cancer diagnosis and treatment, and consequently, patient survival. However, the risk of secondary malignancies owing to radiation exposure remains a matter of concern. We previously published three hybrid computational fetal phantoms, which contained 27 fetal organs, as a starting point for developing the whole hybrid computational pregnant phantom set, which is the final objective of this study. An International Commission on Radiological Protection (ICRP) reference female voxel model was converted to a non-uniform rational B-spline (NURBS) surface model to construct a hybrid computational female phantom as a pregnant mother for each fetal model. Both fetal and maternal organs were matched with the ICRP- 89 reference data. To create a complete standard pregnant computational phantom set at 20, 30, and 35 weeks of pregnancy, the model mother's reproductive organs were removed, and fetal phantoms with appropriate placental and uterine models were added to the female pelvis using a 3D-modeling software. With the aid of radiological image sets that had originally been used to construct the fetal models, each fetal position and rotation inside the uterus were carefully adjusted to represent the real fetal locations inside the uterus. The major abdominal soft tissue organs below the diaphragm, namely the small intestine, large intestine, liver, gall bladder, stomach, pancreas, uterus, and urinary bladder, were removed from non-pregnant females. The resulting fetal phantom was positioned in the appropriate location, matching the original radiological image sets. An obstetrician-gynecologist reviewed the complete internal anatomy of all fetus phantoms and the pregnant women for accuracy, and suggested changes were implemented as needed. The remaining female anatomical tissues were reshaped and modified to accommodate the location of the fetus inside the uterus. This new series of hybrid computational pregnant phantom models provides realistic anatomical details that can be useful in evaluating fetal radiation doses in pregnant patients undergoing diagnostic imaging or radiotherapy procedures where realistic fetal computational human phantoms are required.

1. Introduction

This is the second paper originating from the dissertation of one of the authors (RM) [1], which is the first paper [2] described the development of a set of hybrid patient-specific fetus phantoms using non-uniform rational B-spline (NURBS) surface models from radiological images.This second paper implements the hybrid fetus phantoms into a publicly available standard reference computational phantom—the International

Commission on Radiological Protection (ICRP) 89 standard [3], which was the best available option during the project. To achieve this, the voxelized ICRP 89 reference phantom was converted into NURBS as described below and the fetus phantom added together with some patient specific anatomy of the mother. Meanwhile, the International Commission on Radiological Protection has released a new reference standard known as ICRP 145 [4] for adult mesh-type reference computational phantoms. This new standard includes more details than ICRP 89 and is already in mesh type surfaces. Interested readers can apply the procedures described below and implement the fetus phantoms in the new standard ICRP 145 using NURBS surface models surfaces.

The National Council on Radiation Protection and Measurements 160 report shows that medical radiation exposure to patients is one of the largest sources of radiation exposure in the United States despite the careful use of medical radiation protection [5]. As of 2009, Computed Tomography (CT) scans were responsible for 75.4% of the effective radiation dose delivered by all imaging procedures in the US. Over the last few years, the number of CT scans has increased by up to 400% over the last few years [6]. The American Association of Physicists in Medicine (AAPM) Radiation Therapy Committee Task Group 36 (TG36) reported in 1995 that up to four thousand pregnant women in the United States receive radiotherapy annually [7]. Invasive cancer is the most common cause of death in women aged 45–84 years, and the most common invasive cancer types in pregnant women are breast cancer, cervical cancer, lymphoma, malignant melanoma, and thyroid cancer [8]. Radiation therapy, surgery, and chemotherapy are the three available methods for the treatment of pregnant women with cancer [9]. The number of patients undergoing radiation therapy has increased because of vast improvements in cancer detection, treatment, and survival rates. However, pregnant patients with cancer who require radiation therapy are at a relatively high risk of secondary malignancies [10, 11]. Many of these concerns also apply to the fetus if the mother is treated with radiation during pregnancy [7].

The evolution of anatomical models for radiation dosimetry and radiation protection dosimetry began between 1910 and the late 1960s (see for example the reviews in [12–14]. These models, known as phantoms, have different designs, sizes, and types to serve different purposes and needs. Because it is difficult to measure the total radiation dose received by the human body that is exposed to external or internal radiation, researchers have developed virtual or computational phantoms to simulate patient human bodies for the purpose of dose measurement. Computational phantoms are classified into three types: stylized, voxelized, and hybrid or boundary representation (BREP) phantoms [14]. The first mathematical or stylized phantoms for pregnant patients were introduced by Stabin *et al* in 1995 for nuclear medicine applications [15]. In 2004, Chen *et al* extended the stylized pregnant female models by modifying them with new reference values from ICRP 89 for ionizing dosimetry calculations [16]. With its basic building shapes and simple surface equations, this model is considered very simple and geometrically flexible. Thus, the model lacks appropriate information regarding the accurate locations and overall shapes of organs to represent a realistic human body [14]. Voxelized phantoms were constructed during the 1980s and the 2000s using whole-body computed tomography (CT) or magnetic resonance (MR) imaging of humans. Voxelized phantoms are composed of many small cubes assembled to represent different anatomical structures in three-dimensional (3D) voxels, where each voxel represents the tissue of interest [17]. Becker *et al* segmented a model of a fetus at 24 weeks of pregnancy from the abdominal MRI of a patient and modified their existing reference female voxel phantom (named Katja) to create a virtual pregnant model for dose calculations [18]. Cech *et al* (2007) also developed a pregnant female model named SILVY, which was derived from MR images of an 89kg woman with a malformed uterus. The 89-kg weight is in close agreement with the typical weight of a pregnant patient at 30 weeks of pregnancy. The MR images of the fetus were replaced with CT images of a 30-week fetus made available by Shi and Xu (2004). The SILVY model was only used for non-ionizing radiation calculations and was limited to the uterus, placenta, fetal soft tissue, and skeleton to investigate the interaction between low-frequency electric and magnetic fields in pregnant women [19]. A recent study constructed a voxel-based phantom with twins at 25 and 35 weeks of pregnancy who underwent positron emission tomography (PET) and CT scans. These models were patient-specific voxel phantoms to estimate the fetal and maternal absorbed dose received from radiation dosimetry, using Monte Carlo simulations [20].

Hybrid phantom models such as those published by Xu *et al* in the 2000s [13] combine voxelized phantoms with stylized phantoms. In these models, organ boundaries and outer body contours are converted to 3D polygon meshes or non-uniform rational B-spline (NURBS) surfaces. Xu *et al* released a set of pregnancy models derived from a CT image set of a 7-month pregnant patient. Although the maternal organs were highly detailed, fetal segmentation was limited to the fetal brain, bones, soft tissues, and the placenta. The fetus was scaled according to the standards set by the International Commission of Radiological Protection (ICRP) to show three different stages of pregnancy [13]. In a recent study, three hybrid phantoms were developed for nuclear medicine applications. The fetal models developed do not reflect the proper fetal position inside the uterus [13–15]. Maynard *et al* developed the University of Florida (UF) family of hybrid phantoms that represent the human fetus from MR and CT images. Although these models were highly detailed, representing most of the anatomical structures of the fetus at different ages, a scaling method (rather than real-world data) was also used to construct the target fetal ages for an average ICRP pregnancy model [21]. Xie *et al* [22] developed computational female and fetal models to study the radiation dose delivered to the fetus and pregnant patients during PET examinations for radiation risk assessment. A series of eight pregnant computational phantom sets was developed, with 35 identified tissues included, to cover the entire pregnancy period. However, the models were constructed by modifying previous computational models and a scaling method was applied. The models were used for radiation dose assessment of fetuses and pregnant patients using positron-emitting radiotracers [23]. In addition, a patient-specific computational phantom was developed for dosimetry calculations using a PET/CT scan of a patient pregnant with twins [24]. Another study by Xie *et al* [25] demonstrated that patient-specific computational models can be created using an automated deep learning–based segmentation algorithm for retrospective radiation dose evaluation during high-dose procedures in a clinical setting and in research studies involving retrospective data analysis. Full-body images of pregnant women are seldom medically necessary, viable, or ethical because of radiation exposure to the developing fetus. While voxel-based models lack anatomical integrity because they rely on voxel size and organ shape adjustments, hybrid phantoms are required to take advantage of 3D surface modeling technology, which offers smooth surfaces and anatomically realistic views to obtain complete body scans of pregnant women.

The average pregnant computational phantom [15–26] was adopted and recommended by the ICRP as a standard pregnant patient. To date, only a limited number of realistic fetal phantoms have been created for each pregnancy stage to demonstrate the stages of fetal development and intrauterine positioning. This study aims to create a hybrid computational female phantom model set for the fetus phantoms developed in a previous study [2] by considering a patient's weight gain, body changes, fetal development, fetal position, and detailed anatomy of the fetus inside the patient's body. This can reflect the detailed patient body, which can lead to developing realistic model sets particular to the standard pregnant computational phantom series so medical physicists can rely on them when estimating the fetal dose.

2. Materials and methods

2.1. Development of fetus phantom set

A set of three fetal ages, 20, 31, and 35 weeks of pregnancy, were chosen as good representatives of fetal organ development in the second and third trimesters. Fetus models were previously developed [1, 2] to represent the middle period of the second and third trimesters. Three computational fetal phantom models were constructed from good quality magnetic resonance (MR) imaging data for each fetus to construct a complete, anatomically accurate fetus, gravid uterus, and placenta. All radiologic images in the DICOM format were anonymized using an approved IRB protocol from the Vidant Medical Center in Greenville, North Carolina. Image segmentation was performed on a clinical contouring tool using Velocity software (Velocity 3.1, Atlanta, GA) to identify the appropriate organs and structures that are more sensitive to radiation for organ dose estimates, following the recommendation of ICRP Publication 60 (ICRP, 2012) [27]. The following fetal tissues and organs were identified: brain, eyes, lenses, trachea, bronchus, liver, heart, lungs, stomach, small intestine, large intestine, gallbladder, kidneys, pancreas, spleen, thymus, thyroid gland, tongue, esophagus, tooth buds, spinal cord, spin, urinary bladder, nasal septum, pituitary gland, and fetal body. As the thyroid and adrenal glands could not be clearly identified in the 20-week imaging set, manual models were created and added based on their suitable locations. All organ segmentations, locations, and overall shapes were verified and approved by an obstetrician-gynecologist and coauthor (KN). For each fetal organ, non-uniform rational B-spline (NURBS) surfaces and polygon meshes were manually generated [2]. The organs modeled as NURBS surfaces were the brain, gallbladder, heart, kidneys, liver, lungs, pancreas, spleen, stomach, thymus, trachea, urinary bladder, uterus, and placenta. The fetal body, skeleton (from CT images), umbilical cord, tongue, tooth buds, and small and large intestines were kept in polygon mesh format.

2.2. Development of standard hybrid female phantom

2.2.1. ICRP reference female

In this study, an adult ICRP reference female phantom in the voxel format [28] was used to construct a hybrid computational pregnant female phantom. The female polygon mesh model was constructed from the voxel model, utilizing a Visualization Toolkit VTK-based marching cubes algorithm for manipulating and displaying 3D rendered objects [29]. This algorithm generates a rendering surface that describes the full geometry of a 3D model using triangular meshes. The stereolithography format (STL), also known as standard triangle language represents a 3D object as a set of interconnected triangular facets that are easy to manipulate [29, 30]. The process started by generating a polygon mesh in STL format for each organ, using VTK to manipulate them, and importing the polygon meshes into a 3D modeling software (Rhinoceros). Triangle mesh representations of the organs of an adult ICRP reference female in STL file format were imported into a readable file format by Rhinoceros [31], with a mesh model resolution of 2 mm × 2 mm × 2 mm. Rhinoceros software was used for geometry verification with the MeshRepair, PatchSingleFace, FillMeshHoles, and RebuildMesh rendering options. The Boolean operator is a very useful tool for separating two surfaces or polygon meshes by creating a space between overlapping organs, as needed. Some female organ models, such as the brain, entire skeletal joints, and vertebrae, were kept in a polygon mesh to maintain the realistic topology of each organ model.

2.2.2. NURBS and polygon mesh modeling

To effectively manipulate the polygon mesh anatomy of the computational phantom, STL files were generated and imported into Rhinoceros in many different layers, which can be turned off and on without interrupting the location of other organs in other layers. To generate an NURBS surface, contouring and lofting tools were used in Rhinoceros. The contours were constructed from native polygon mesh organs by creating a spaced series of planar curves through the polygon mesh surface. This was used to generate NURBS surfaces from those contours by fitting surfaces through those curves to define and match the same native surface shape. NURBS surfaces were generated in the lungs, heart, thyroid glands, thymus, spleen, liver, stomach, kidneys, adrenal glands, gallbladder, pancreas, urinary bladder, and uterus. The essential step in this process is that the final NURBS surfaces must be made to precisely match the polygon mesh surfaces such that the original anatomy of each NURBS surface is preserved without creating surface collisions between adjacent organs. In some cases, manual adjustments are necessary to prevent overlapping collisions during the 3D modelling process. Eyeballs and lenses were later replaced with spherical and ellipsoidal shapes to achieve smooth 3D modeling surfaces that were otherwise insufficiently modeled by the resolution of the original MRI data. Some organs are modeled by their walls and contents, such as the gallbladder and the small and large intestines. The most effective way to extract the contents from their walls is to proportionally reduce the generated NURBS surfaces and create another NURBS surface that is smaller than the contents [12]. The NURBS surfaces for the breasts were modeled based on the initial female polygon anatomy and then replaced by matching the NURBS surfaces.

The NURBS surfaces of the small and large intestines were designed differently than the other organs using the pipe command in Rhinoceros. Uniform pipe NURBS surfaces were inserted manually from a single line to build cylindrical pipes that matched the polygon mesh volume and location of the original small and large intestines. The small intestine, including the duodenum, jejunum, and ileum, starts at the outlet of the stomach and ends at the beginning of the large intestine. The large intestine, including the ascending, transverse, descending, and sigmoid colon, starts at the termination of the small intestine and ends at the rectum. Two pipes were modelled using the same single line to build the contents and walls of the intestines. It took approximately one month to design the small and large intestines and to successfully fit them with the mother's internal organs for each pregnancy period.

2.2.3. Standard hybrid female phantom

Matching the NURBS or polygon mesh surfaces of the adult ICRP reference female model with the corresponding original adult female ICRP reference phantom reported in the ICRP 110 report is an essential step [28]. The masses and densities of organs and tissues were recorded in the ICRP reference data. Densities from ICRU Report 46 [32] are reported in table A.1 of ICRP 110 and were used to calculate the organ mass reference values in ICRP 89. Therefore, the female NURBS and polygon organs and tissues generated from the voxel model were individually matched with the reference values provided in the ICRP 89 Publication [33]. The best way to match the ICRP reference values was to use the 3D Scale command in Rhinoceros. Another way to approach the same ICRP reference values is to use control points controlled by NURBS in 3D modelling. To preserve realistic human organs and tissues, it was easier to manipulate the control points than using the 3D scale tool. Meticulous attention has been devoted to constructing organ walls and their contents, such as the gallbladder, small intestine, and large intestine. The scaling method was applied to the entire group to eliminate any gaps between organs. Figure 1 illustrates the front and back views of the standard female reference model after the skin was removed from the original voxels in a polygon mesh. The original voxels were converted to NURBS surface representation using Rhinoceros software.

2.2.4. Pregnant female phantom construction

Both the standard computational female model and fetus phantom sets developed in NURBS or polygon mesh were used to construct a pregnant model set at three different pregnancy periods. Major abdominal soft tissue organs below the diaphragm were completely removed from non-pregnant females using Rhinoceros software: the small intestine, large intestine, liver, gall bladder, stomach, pancreas, uterus, and uterine bladder. The finished fetus phantoms were positioned in the appropriate locations, matching the original radiological image sets. The flexible nature of the NURBS or polygon mesh format of these phantoms has significant advantages because their shape and volume can be changed to match the original MR image data.

2.2.5. Pregnant female phantom—20 weeks

To construct a hybrid computational pregnant phantom model at 20 weeks of pregnancy, the first step was to remove maternal soft organs and tissues using Rhinoceros software. The second step was to add the

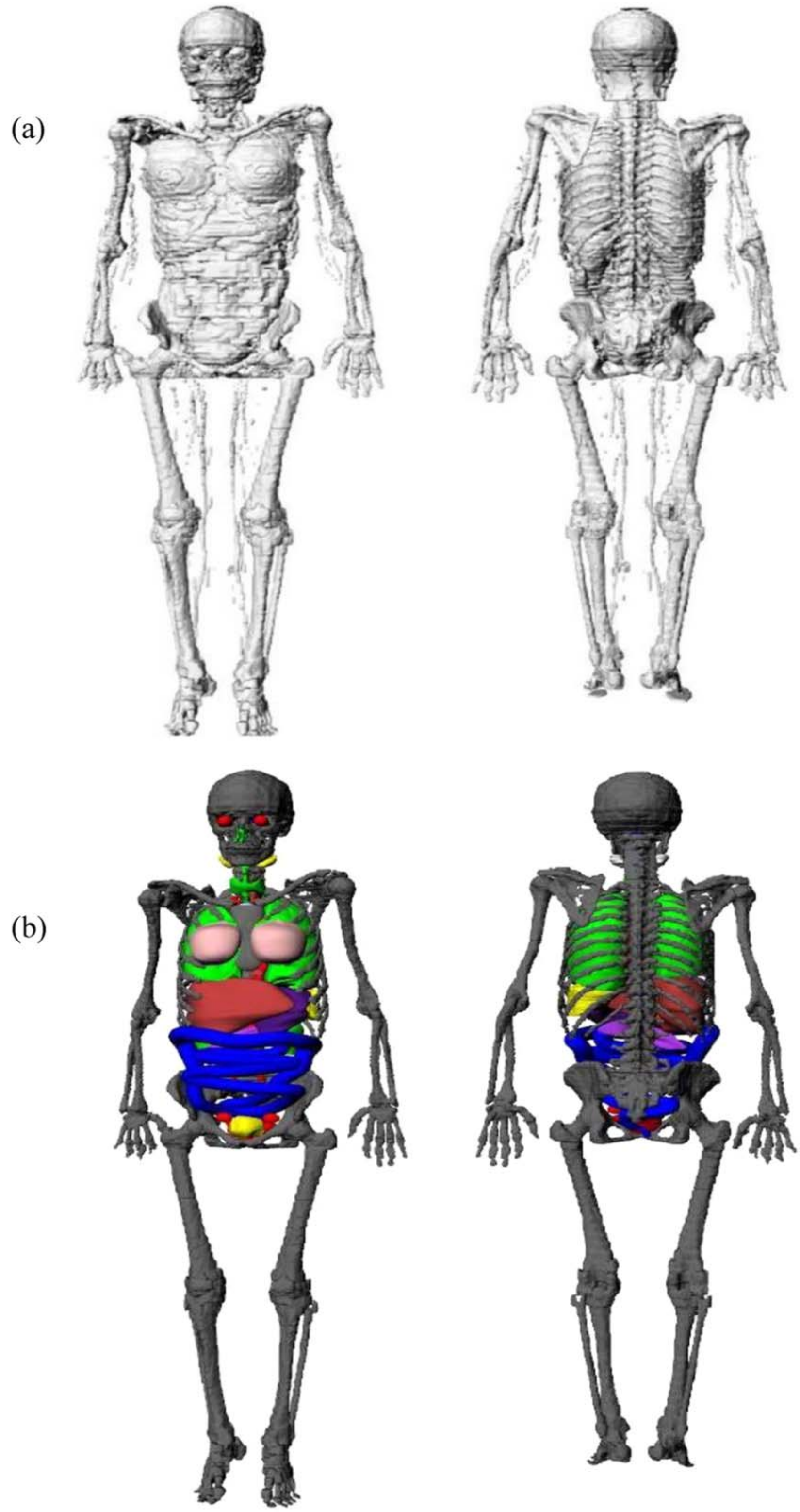

Figure 1. Front and back views of the standard reference female model after removing the skin (a) from the original voxels in a polygon mesh and (b) after convert the original voxels to NURBS surface representation using Rhinoceros software.

maternal uterus and the finished 20-week fetus to the finished female adult ICRP reference model. As a starting point, it was best to locate the maternal uterus and its contents roughly where the model's uterus had been, and then to use the radiological MR image set as a guide to adjust the location of the mother's uterus and the fetus phantom. Once the 20-week fetal phantom model closely matched the corresponding location of the fetus in the radiological image set, the remaining maternal organs were gradually added to complete the pregnant phantom model. In this process, however, some adjustments were necessary,

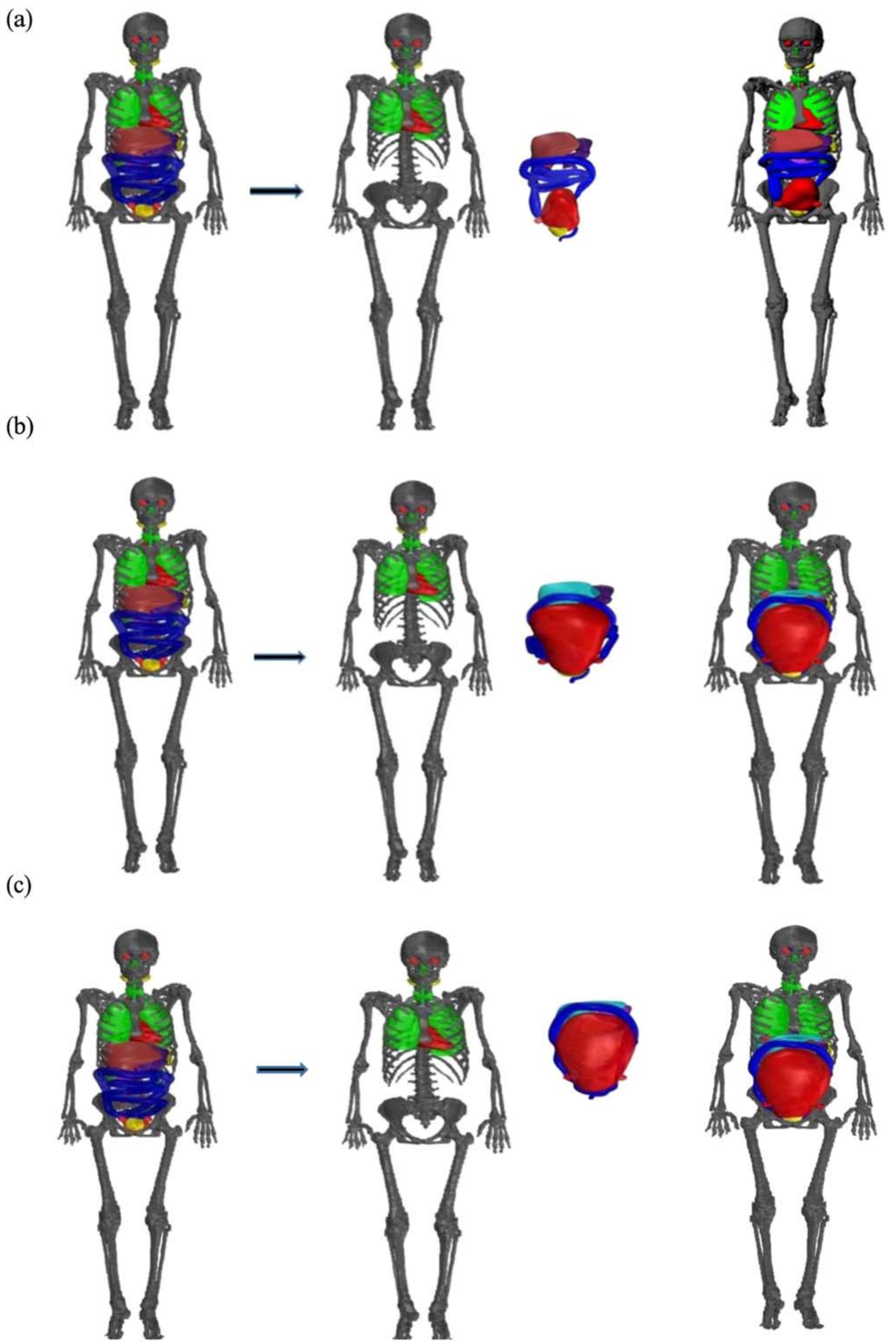

Figure 2. The steps required to create an ICRP pregnant computational phantom set by adding the new fetus phantom to the ICRP reference female after removing selected organs from the non-pregnant model at (a) 20, (b) 31, and (c) 35 weeks of gestation.

such as moving the small and large intestines slightly away from the uterus, thereby creating sufficient space for the 20-week fetal phantom to fit without any overlaps. Because at the 20-week stage, the fetus was small, limited soft tissue modification was required for this model. The only maternal organs that required modification were the uterus, ovaries, urinary bladder, large intestine, and small intestine. During pregnancy, the maternal female glandular tissue structure remains unchanged from that of the ICRP reference female [33].

2.2.6. Pregnant female phantom—31 weeks

A 31-week pregnant female model was developed by matching the ICRP female phantom model and adding the developed 31week fetal phantom. The abdomen of the female phantom was completely removed, and the developed uterus and its 31-week

Table 1. An Adult ICRP reference female mass, volume, and density [3, 32].

Female Phantom	Density ($g\,cm^{-3}$)	ICRP Mass (g)	ICRP-89 Female Volume (mm3)	Female Phantom Volume (mm3)	NURBS or Mesh
Adrenals (2)	1.03	13.00	12600.00	12429.58	mesh
Brain	1.05	1300.00	1238100.00	1190671.42	nurbs
Breast Exterior (2)	0.98	172.54	176647.00	176647.00	nurbs
Breast glands (2)	0.98	500.00	511900.00	512532.00	mesh
Branchi	1.07	—	—	246.84	nurbs
Eyeballs (2)	1.05	15.00	14300.00	14215.98	nurbs
Eye Lenses (2)	1.00	0.40	400.00	395.55	nurbs
Gall Bladder wall	0.81	8.00	9900.00	9996.10	nurbs
Gall Bladder Content	1.08	48.00	54300.00	53977.19	nurbs
Gall Bladder Contents	1.08	48.00	54300.00	53977.19	nurbs
Heart	1.06	620.00	587200.00	578900.09	nurbs
Small Intestine Wall	1.03	600.00	582500.00	575176.00	nurbs
Small Intestine Content	1.03	280.00	280000.00	278013.00	nurbs
Large Intestine Wall	1.04	360.00	414839.16	414839.16	nurbs
Large Intestine Contents	1.04	320.00	239916.50	239916.50	nurbs
Kidneys (2)	1.05	275.00	261900.00	260332.73	nurbs
Larynx	1.07	19.00	17750.00	17658.00	nurbs
Liver	1.05	1400.00	1333300.00	1345840.15	nurbs
Liver	1.05	1400.00	1333300.00	no change	nurbs
Lungs (2)	0.41	950.00	2300800.00	2309763.00	mesh
Nasal septum	1.03	—	—	4363.00	mesh
Esophagus	1.03	35.00	34000.00	33811.00	nurbs
Ovaries (2)	1.04	11.00	10600.00	10479.00	nurbs
Pancreas	1.05	120.00	116500.00	115573.00	nurbs
Pituitary gland	1.00	0.60	600.00	607.04	nurbs
Pharynx	1.03	—	12166.87	12166.00	mix
Skeleton (total)	1.03	7800.00	7572800.00	7262189.62	—
Skin	1.10	2300.00	2496800.00	—	nurbs
Spleen	1.04	130.00	125000.00	12439.79	mesh
Spinal cord	1.02	—	—	17432.00	mesh
Spine	1.03	—	—	1015507.00	nurbs
Stomach wall	1.03	140.00	135922.00	137261.87	nurbs
Stomach contents	1.00	230.00	230000.00	228307.43	mesh
Tongue	1.05	60.00	57100.00	56844.00	mesh
Tooth Buds	2.74	40.00	14600.00	14698.59	mesh
Tonsils (2)	1.03	3.00	2900.00	2895.48	nurbs
Trachea	1.07	8.00	7740.00	7801.36	nurbs
Thymus	1.03	20.00	18700.00	18672.59	nurbs
Thyroid Gland	1.04	17.00	16100.00	16053.37	nurbs
Total Body	1.01	60000.00	59257999.77	59257999.77	nurbs
Urinary Bladder	1.04	40.00	38500.00	38942.00	nurbs
Uterus	1.03	80.00	77700.00	77700.00	nurbs

fetal phantom were added to the female pelvis. The remaining female anatomical tissues were reshaped and modified to match the shape of the abdomen at 31 weeks of pregnancy. This process requires a lot of work because, at this stage of pregnancy, the fetus is bigger, and the position and shape of most of the mother's internal organs have changed to accommodate the growing fetus. New small and large intestines were modeled, along with internal and external wall construction for each intestine. Figure 2 shows a model of the finished fetus inside the uterus. A control point technique was used to modify the urinary bladder, gall bladder, stomach, spleen, and liver. The Boolean operator is a useful tool for separating the overlapping organs and tissues. These organs and tissues were modified based on the original MR image set used to construct the 31-week phantom, which reflected the real anatomical organs. The modified organs and tissues were used instead of the native organs and tissues of the female phantom. The location of the 31-week fetal phantom is inferior to that of the 20-week fetal phantom in the mother's pelvis. This is due to the gradual development of the lower uterine segment, which is the physiological funneling of the uterus. This change also pushed the location of the urinary bladder in the anterior direction. At 31 weeks of pregnancy, the glandular tissue structure of the maternal female was larger than that of the ICRP reference female; thus, changes were made to match the overall breast size in the MR images. Finally, the resulting fetal model was confirmed by an OBGYN specialist.

Table 2. 20-week pregnant female phantom model mass, volume, and density[3, 32].

20-Weeks pregnant female phantom	Density ($g\,cm^{-3}$)	ICRP mass (g)	ICRP-89 female volume (mm3)	Pregnant female volume (mm3)	Modified organs Yes/No
Adrenals (2)	1.03	13.00	12600.00	12429.58	—
Brain	1.05	1300.00	1238100.00	1190671.42	—
Breast Exterior (2)	0.98	500.00	511900.00	275809.09	Yes
Breast glands (2)	0.98	172.54	176647.00	95059.16	Yes
Breast-Total	0.98	360.00	367346.94	370868.25	Yes
Branchi	1.07	—	—	246.84	—
Eyeballs (2)	1.05	15.00	14300.00	14215.98	—
Eye Lenses (2)	1.00	0.40	400.00	395.55	—
Gall Bladder Wall	1.08	48.00	54300.00	53988.19	Yes
Gall Bladder Content	0.81	8.00	9900.00	9991.11	Yes
Heart	1.06	620.00	587200.00	578900.09	—
Small Intestine Wall	1.03	600.00	582500.00	353308.87	Yes
Small Intestine Content	1.03	280.00	280000.00	394406.34	Yes
Large Intestine Wall	1.04	360.00	414839.16	414839.16	Yes
Large Intestine Contents	1.04	320.00	239916.50	239916.50	Yes
Kidneys (2)	1.05	275.00	261900.00	260332.73	—
Larynx	1.07	19.00	17750.00	17658.00	—
Liver	1.05	1400.00	1333300.00	1345840.15	—
Lungs (2)	0.41	950.00	2300800.00	2309763.00	—
Nasal septum	1.03	—	—	4363.00	—
Esophagus	1.03	35.00	34000.00	33811.00	—
Ovaries (2)	1.04	11.00	10600.00	10479.00	—
Pancreas	1.05	120.00	116500.00	115573.00	—
Pituitary gland	1.00	0.60	600.00	607.04	—
Pharynx	1.03	—	12166.87	12166.00	—
Skeleton (total)	1.03	7800.00	7572800.00	7262189.62	—
Skin	1.10	2300.00	2496800.00	—	—
Spleen	1.04	130.00	125000.00	12439.79	—
Spinal cord	1.02	—	—	17432.00	—
Spine	1.03	—	—	1015507.00	—
Stomach Wall	1.03	140.00	135922.00	227498.09	Yes
Stomach Contents	1.00	230.00	230000.00	136860.15	Yes
Tongue	1.05	60.00	57100.00	56844.00	—
Tooth Buds	2.74	40.00	14600.00	14698.59	—
Tonsils (2)	1.03	3.00	2900.00	2895.48	—
Trachea	1.07	8.00	7740.00	7801.36	—
Thymus	1.03	20.00	18700.00	18672.59	—
Thyroid Gland	1.04	17.00	16100.00	16053.37	—
Total Body	1.01	—	—	66607584.00	Yes
Urinary Bladder	1.04	40.00	38500.00	38528.47	Yes
Uterus	1.03	80.00	77700.00	988426.31	Yes

2.2.7. Pregnant female phantom—35 Weeks

The realistic anatomy of the whole-body pregnant phantom was developed by combining the newly constructed fetal phantom at 35 weeks of pregnancy with the deformed ICRP female phantom model. After removing the abdominal organs of the ICRP female phantom, a 35-week fetal phantom was added. The fetus is large at this stage and is located differently in the pelvis than at 31 weeks of pregnancy. In this model, many maternal organs were modeled de novo, such as the small and large intestines and urinary bladder, whereas other maternal organs were modified, such as the liver, stomach, spleen, and gall bladder. The fetal body, placenta, and umbilical cord inside the mother's uterus were positioned according to the original MR image set that had been used. Many factors had to be considered in order to build an accurate representation of a 35-week pregnant woman's shape, especially regarding the abdominal area, and to adjust the mother's posture and fetal location inside the uterus. At 35 weeks of pregnancy, the total glandular tissue structure of the maternal female was modified to match the original MR images.

3. Results

3.1. Comparing fetal organ masses with ICRP recommendations

The voxelized ICRP adult reference female in polygon mesh format and the computational ICRP adult

Table 3. 31-week pregnant female phantom model mass, volume, and density [3, 32].

31-Weeks pregnant female phantom	Density (g cm^{-3})	ICRP mass (g)	ICRP-89 female volume (mm3)	Pregnant female volume (mm3)	Modified organs Yes/No
Adrenals (2)	1.03	13.00	12600.00	12429.58	—
Brain	1.05	1300.00	1238100.00	1190671.42	—
Breast Exterior (2)	0.98	500.00	511900.00	559406.24	Yes
Breast glands (2)	0.98	172.54	176647.00	192802.52	Yes
Breast-Total	0.98	740.00	755102.04	752208.76	Yes
Branchi	1.07	—	—	246.84	—
Eyeballs (2)	1.05	15.00	14300.00	14215.98	—
Eye Lenses (2)	1.00	0.40	400.00	395.55	—
Gall Bladder Wall	1.08	48.00	54300.00	52316.83	Yes
Gall Bladder Content	0.81	8.00	9900.00	9973.39	Yes
Heart	1.06	620.00	587200.00	578900.09	—
Small Intestine Wall	1.03	600.00	582500.00	369071.05	Yes
Small Intestine Content	1.03	280.00	280000.00	377973.82	Yes
Large Intestine Wall	1.04	360.00	414839.16	522943.70	Yes
Large Intestine Contents	1.04	320.00	239916.50	160635.00	Yes
Kidneys (2)	1.05	275.00	261900.00	260332.73	—
Larynx	1.07	19.00	17750.00	17658.00	—
Liver	1.05	1400.00	1333300.00	1305443.47	Yes
Lungs (2)	0.41	950.00	2300800.00	2309763.00	—
Nasal septum	1.03	—	—	4363.00	—
Esophagus	1.03	35.00	34000.00	33811.00	—
Ovaries (2)	1.04	11.00	10600.00	10479.00	—
Pancreas	1.05	120.00	116500.00	108044.43	Yes
Pituitary gland	1.00	0.60	600.00	607.04	—
Pharynx	1.03	—	12166.87	12166.00	—
Skeleton (total)	1.03	7800.00	7572800.00	7262189.62	—
Skin	1.10	2300.00	2496800.00	—	—
Spleen	1.04	130.00	125000.00	12439.79	—
Spinal cord	1.02	—	—	17432.00	—
Spine	1.03	—	—	1015507.00	—
Stomach Wall	1.03	140.00	135922.00	225502.48	Yes
Stomach Contents	1.00	230.00	230000.00	137234.79	Yes
Tongue	1.05	60.00	57100.00	56844.00	—
Tooth Buds	2.74	40.00	14600.00	14698.59	—
Tonsils (2)	1.03	3.00	2900.00	2895.48	—
Trachea	1.07	8.00	7740.00	7801.36	—
Thymus	1.03	20.00	18700.00	18672.59	—
Thyroid Gland	1.04	17.00	16100.00	16053.37	—
Total Body	1.01	—	—	78907984.00	Yes
Urinary Bladder	1.04	40.00	38500.00	38082.51	Yes
Uterus	1.03	80.00	77700.00	4539852.80	Yes

reference female phantom modeled on the NURBS surfaces were completed. Front and back views of the ICRP adult reference female in NURBS surfaces are shown in figure 1, and all volume and mass values of the developed female models were matched with the reference data provided in the ICRP 89 Publication, as shown in table 1. In figure 2, three-dimensional representations of the hybrid fetus phantom models at 20, 31, and 35 weeks of pregnancy are presented. This shows the steps necessary to add fetal phantoms to the maternal uterus to create the pregnant phantom model sets. All volumes and mass values of the pregnant female models were matched with the reference data provided in the ICRP 89 publication [3]. The mass and density values are listed in tables 2–4.

3.2. Fetus position in utero

The radiation dosimetry literature does not specify the fetal posture or orientation in earlier models. Throughout pregnancy, the fetus is actively mobile, with an increased likelihood of being discovered head-down as pregnancy continues to term. To ensure accurate and consistent modeling, all fetal placements were meticulously changed to mirror the original position of the fetus within the mother uterus [2]. All fetal models were head-down, with the 20-week pregnancy model in the right occiput posterior (ROP) configuration, the 31-week gestation model in the left occiput anterior (LOA) configuration, and the 35-week gestation model in the ROP configuration, all surrounded by maternal tissues, including the placenta and uterus [1].

Table 4. 35-week pregnant female phantom model mass, volume, and density [3, 32].

35-Weeks pregnant female phantom	Density (g cm^{-3})	ICRP mass (g)	ICRP-89 female volume (mm3)	Pregnant female volume (mm3)	Modified organs Yes/No
Adrenals (2)	1.03	13.00	12600.00	12429.58	—
Brain	1.05	1300.00	1238100.00	1190671.42	—
Breast Exterior (2)	0.98	500.00	511900.00	576529.75	Yes
Breast glands (2)	0.98	172.54	176647.00	198704.24	Yes
Breast-Total	0.98	760.00	775510.20	775233.98	Yes
Branchi	1.07	—	—	246.84	—
Eyeballs (2)	1.05	15.00	14300.00	14215.98	—
Eye Lenses (2)	1.00	0.40	400.00	395.55	—
Gall Bladder Wall	1.08	48.00	54300.00	53977.19	Yes
Gall Bladder Content	0.81	8.00	9900.00	9996.20	Yes
Heart	1.06	620.00	587200.00	578900.09	—
Small Intestine Wall	1.03	600.00	582500.00	399158.34	Yes
Small Intestine Content	1.03	280.00	280000.00	327297.39	Yes
Large Intestine Wall	1.04	360.00	414839.16	525786.55	Yes
Large Intestine Contents	1.04	320.00	239916.50	276335.90	Yes
Kidneys (2)	1.05	275.00	261900.00	260332.73	—
Larynx	1.07	19.00	17750.00	17658.00	—
Liver	1.05	1400.00	1333300.00	1220959.04	Yes
Lungs (2)	0.41	950.00	2300800.00	2309763.00	—
Nasal septum	1.03	—	—	4363.00	—
Esophagus	1.03	35.00	34000.00	33811.00	—
Ovaries (2)	1.04	11.00	10600.00	10479.00	—
Pancreas	1.05	120.00	116500.00	117237.47	Yes
Pituitary gland	1.00	0.60	600.00	607.04	—
Pharynx	1.03	—	12166.87	12166.00	—
Skeleton (total)	1.03	7800.00	7572800.00	7262189.62	—
Skin	1.10	2300.00	2496800.00	—	—
Spleen	1.04	130.00	125000.00	12439.79	—
Spinal cord	1.02	—	—	17432.00	—
Spine	1.03	—	—	1015507.00	—
Stomach Wall	1.03	140.00	135922.00	205160.76	Yes
Stomach Contents	1.00	230.00	230000.00	128294.25	Yes
Tongue	1.05	60.00	57100.00	56844.00	—
Tooth Buds	2.74	40.00	14600.00	14698.59	—
Tonsils (2)	1.03	3.00	2900.00	2895.48	—
Trachea	1.07	8.00	7740.00	7801.36	—
Thymus	1.03	20.00	18700.00	18672.59	—
Thyroid Gland	1.04	17.00	16100.00	16053.37	—
Total Body	1.01	60000.00	59257999.77	79936609.20	Yes
Urinary Bladder	1.04	40.00	38500.00	17562.78	Yes
Uterus	1.03	80.00	77700.00	5181572.78	Yes

4. Discussion

Three state-of-the-art hybrid computational pregnant phantom models were developed based on the advanced polygon mesh and NURBS surface methods. The pregnant models were developed in this study by applying these methods to the adult ICRP reference voxelized female phantom and three segmented computational fetal phantoms that were previously published [1, 2]. As shown in figure 2, distinguishing most of the female internal soft organs was difficult because the outlines of the organs were lines with gaps that were not always smooth and visible. The original voxel size of the ICRP female model was 2 mm × 2 mm × 2 mm. In reverse view, the lines representing the bones and skeleton of the ICRP female were continuous and smooth; therefore, they were left in polygon mesh representation. The voxelized reference female in the polygon mesh model was constructed using the Visualization Toolkit VTK-based marching cube algorithm [29]. This algorithm generates a rendering surface that describes the full geometry of the 3D model in a triangular mesh, as shown in figure 2 [29, 30]. Gaussian filters were applied to smooth the organ shapes; however, these filters caused differences, especially in organ size. These organs were later corrected and matched with the ICRP adult female reference data [28]. Most organs and tissues were converted in NURBS surface modeling, except for a few organs that were kept in polygon mesh, such as the brain, all the joints of the skeleton, and the vertebrae, to maintain the realistic topology of each organ feature model. The NURBS surfaces in the computational female and fetal phantoms enhanced the continuity

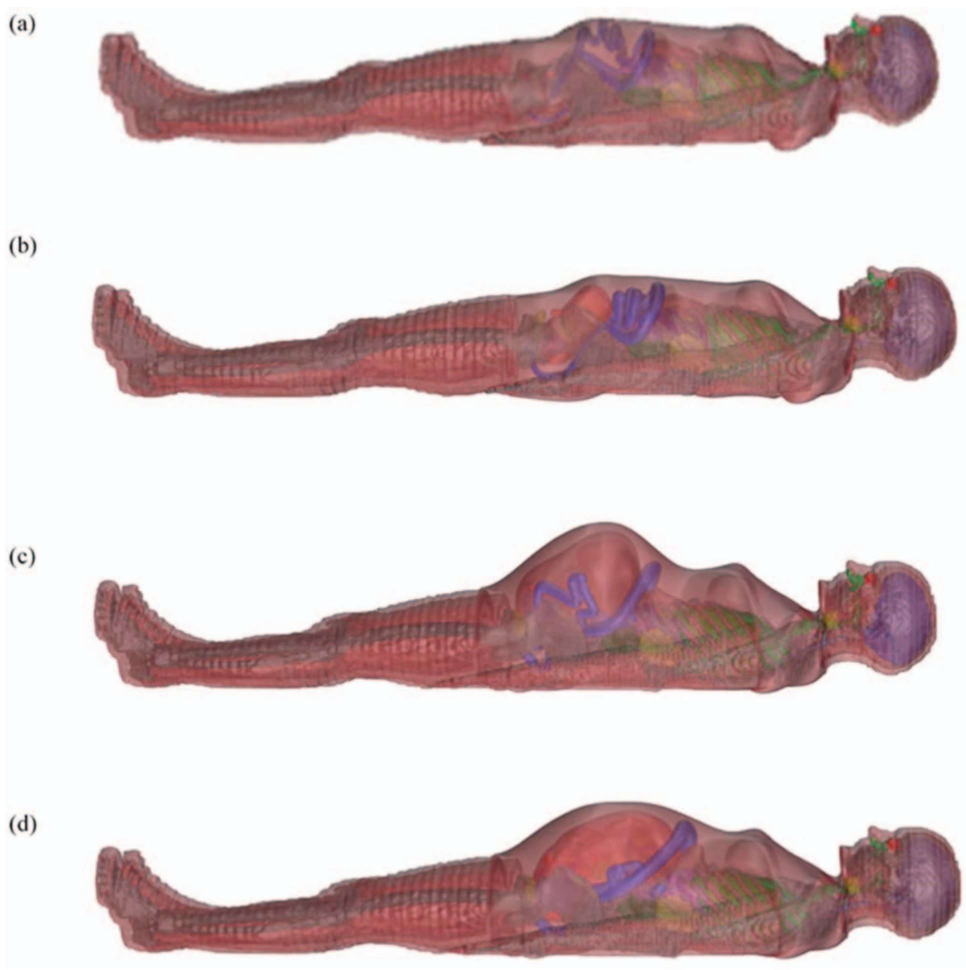

Figure 3. Side and the original views of pregnant female phantom series. (a) ICRP female phantom, (b) 20-week pregnant phantom, (c) 31-week pregnant phantom, (d) 35-week pregnant phantom [31].

and overall smoothness of the internal anatomy of the soft organs, as shown in figure 2. The surfaces of the NURBS-based phantom were defined using a set of control points. The shape and volume of an NURBS surface vary according to the coordinates of the control points. The polygonal mesh has three remarkable advantages for the development of whole-body phantoms. Bones and skeletons were left in mesh surfaces, showing the human anatomy, to obtain real patient anatomical images or commercial human anatomy mesh models. For radiation transport simulation studies, computational phantoms in NURBS surfaces were directly implemented in the code for radiation simulation studies [17]. The final pregnant model set had a height of 168 cm and weight of 60 kg, with over 140 organs and tissues. The fetus can be located at different angles inside the mother's uterus. In general, in the occiput position, the baby's head is directed towards the pelvis, and the baby is facing the mother's abdomen. *A posterior* presentation aims the top of the head into the pelvis. In the anterior position, the baby's headfirst enters the pelvis with the crown of the head. In this study, the 20-, 31-, and 35-weeks fetus models were all head-down models. While both the 20- and 35-week fetal models were in a right occiput posterior (ROP) configuration, the 31-week fetal model was in the left occiput anterior (LOA) position, surrounded by maternal tissue, including the placenta and uterus. Fetal organ and female organ volume adjustments were necessary to match the average reference values reported in the ICRP 89 Publication within 1% [3]. The complete fetal anatomy was reviewed by a clinical obstetrician and facility specialist, and the suggested modification was applied. With the aid of radiological image sets that were originally used to construct the fetal models, each fetal position and rotation inside the uterus was adopted.

5. Conclusion

The goal of this project was to develop methods to accurately estimate fetal dose. Our initial work was to develop a realistic computational fetal phantom model derived from human pregnant patients. In this study, which is the second goal of this project, aims to combine an adult ICRP reference female computational model with the fetal models that we have developed. A total of 35 different organs and tissues were identified from the reference voxel female model. The three hybrid computational fetal phantoms were individually added to the adult ICRP reference female NURBS surface or polygon mesh model to create three realistic hybrid computational pregnant phantom models. Some maternal organs were either modified or remodeled using radiological images. The masses of the maternal organs and tissues were re-matched with the ICRP reference values (original voxel model). It is important to mention that the new pregnant female phantom models created in this study represent improvements in the anatomical representation of the developing fetus, particularly with respect to individual fetal soft tissues and organs for each fetal model, because they are constructed from real radiological image sets from pregnant patients for each pregnancy period. The newly pregnant phantom set included all the factors that could contribute to the fetal dose. Such factors include the weight a patient has gained, patient body changes, fetal development, fetal position, and detailed anatomy of the fetus inside the patient's body, which can be accomplished using the MR of pregnant patients. This can reflect the detailed patient body, which can lead to designing realistic model sets that are specific to the standard pregnant computational phantom series so that the field of medical physics can rely on them in the future when estimations regarding the fetal dose are made to avoid any future cancer in the patient or fetus, as shown in figure 3.

Acknowledgments

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IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418.

IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418.

Data availability statement

No new data were created or analysed in this study.

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