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ORIGINAL ARTICLE

Hybrid 3D pregnant woman and fetus modeling from medical imaging for dosimetry studies

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Abstract
Purpose Numerical simulations studying the interactions between radiations and biological tissues require the use of three-dimensional models of the human anatomy at various ages and in various positions. Several detailed and flexible models exist for adults and children and have been extensively used for dosimetry. On the other hand, progress of simulation studies focusing on pregnant women and the fetus have been limited by the fact that only a small number of models exist with rather coarse anatomical details and a poor representation of the anatomical variability of the fetus shape and its position over the entire gestation.
Methods In this paper, we propose a new computational framework to generate 3D hybrid models of pregnant women, composed of fetus shapes segmented from medical images and a generic maternal body envelope representing a synthetic woman scaled to the dimension of the uterus. The computational framework includes the following tasks: image segmentation, contour regularization, mesh-based surface reconstruction, and model integration.
Results A series of models was created to represent pregnant women at different gestational stages and with the fetus in different positions, all including detailed tissues of the fetus and the utero-fetal unit, which play an important role in dosimetry. These models were anatomically validated by clinical obstetricians and radiologists who verified the accuracy and representativeness of the anatomical details, and the positioning of the fetus inside the maternal body.
Conclusion The computational framework enables the creation of detailed, realistic, and representative fetus models from medical images, directly exploitable for dosimetry simulations.

Keywords 3D Modeling · Segmentation · Fetus · Ultrasound · MRI · Dosimetry

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Introduction

Several organizations and institutes like the World Health Organization (WHO), the European Cooperation in the Field of Scientific and Technical Research (COST 281) or the Mobile Manufacturers Forum (MMF), have confirmed that the study of interactions between radio frequency waves and biological tissues requires precise models of the human body at various ages.

Realistic and precise human head models were previously developed by our group, based on magnetic resonance image (MRI) data, for adults [1] and children [2,3] to study the impact of mobile phones on cerebral tissues. With hand-free kits and the exposure of some professionals to magnetic fields, whole human body models and fetus models are now needed for dosimetry studies. Dosimetry refers to numerical simulations computing the dose absorbed by body tissues resulting from the exposure to some specified radiations. Given an anatomical model of a human body, a standard method used to compute the absorbed dose is described in [4]. For dosimetry studies, body models must have smooth transitions between labeled structures to avoid numerical instabilities during dose propagation simulations. They also need

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to be realistic, including detailed information on the tissue localizations and the organ shapes. For example, if the fetus body is considered as homogeneous and made of a single tissue type, dosimetry simulations can lead to an overestimation or underestimation of the absorbed dose if assigning an average absorption rate to the whole fetus.

Few models of pregnant women were previously developed in the context of dose simulation or dosimetry, with limited anatomical details on the utero-fetal unit. In this paper, we present a set of nine pregnant woman models with detailed, representative, and realistic utero-fetal structures at various stages of gestation and in different positions. These models intend to complement the set of existing models which all have advantages and limitations. Models of the utero-fetal unit were created from segmentations of MRI and ultrasound (US) image data, acquired during regular clinical follow-ups, and embedded in a synthetic maternal body shape provided by the computer graphics software tool DAZ Studio (http://www.daz3d.com).

After reviewing the state of the art in terms of pregnant woman modeling, we describe our medical image database and the proposed computational framework to create realistic models with detailed utero-fetal units. Visual illustrations of some models generated in this study are finally provided and discussed.

State of the art

Anatomical models used in dosimetry studies can be classified into four categories as follows:

1. Mathematical (stylized) models, for which organs are represented with surface equations. These models enable fast dosimetry simulations and are easily deformable and scalable, but only represent an over-simplified anatomy;
2. Synthetic models created by the computer graphics community;
3. Voxelized models, extracted from detailed segmentation of medical images, which precisely represent the anatomy. However, deforming and manipulating such models is challenging since rigid structures (such as bones) and elastic structures (such as the skin, muscles, fat …) must be morphed simultaneously. Moreover, the segmentation of a medical image dataset only reflects the anatomy of a single individual and the corresponding model might not be representative of a population; and
4. Hybrid models, combining voxelized models with either mathematical models or synthetic models.

The first published pregnant woman model was the mathematical model used in [5], in the context of limited computational power and limited obstetrical image quality that could not provide suitable data to build voxelized models. Only three pregnant females, at 3, 6, and 9 months of gestation were represented with these models. In this work, we want to provide models at different stages of gestation. In addition, these models were computed with primitive shapes and were not realistic. On the contrary, we propose a computational framework to generate realistic pregnant woman models from the segmentation of medical images.

With the advent of fast computerized tomography (CT) and MRI acquisition protocols that enable whole-body scanning, several voxelized models of the human body are nowadays available, for adults and children [6], which have enabled extensive dosimetry studies. However, gathering whole body image data on a pregnant woman is not feasible due to ethical reasons. Therefore, hybrid models need to be built, merging mathematical models, synthetic models, and/or voxelized models.

In [7], a voxelized model was built from a single CT data set. The fetus model was rather coarse due to a large image slice thickness (7 mm) and only fetal soft tissues and skeleton were distinguished. The pregnant woman model was truncated, since the CT image only included the patient's torso.

In [8], segmentation of the maternal trunk, the uterus and the gestational sac (when visible) on CT data enabled the authors to generate a simplified utero-fetal unit, distinguishing soft tissues from bones. In our work, we chose to model several fetal tissues and organs (eyes, brain, lung, heart, etc.), but were not able to include the bones yet. In this respect, this previous model and our models complement well each others. Moreover, the authors modeled the fetuses only after the 12th week of gestation, whereas we modeled embryos at 8th week of gestation, using 3D ultrasound data. On the other hand, some of these models represented the fetus during the second trimester of pregnancy while we lack image data during this period of gestation. Indeed, contrary to this previous work, we used MRI and 3D ultrasound data, which are routine screening modalities for pregnant women.

The hybrid model SILVY was presented in [9], by combining MRI data of a malformed fetus with the voxelized model of [7] and completing the woman body by adding legs, arms, and a head taken from a synthetic model.

The uterus and fetus mathematical models of [10] at 13, 26, and 38 weeks of gestation were embedded in the non-pregnant model NAOMI [11]. This embedding involved voxel editing of NAOMI which induced variations in organs shapes and volumes. Moreover, the brain was the unique fetal organ being detailed.

In [12], a synthetic model of the uterus and the fetus was embedded in a woman computer-graphics model. A set of pregnant-woman models at each month of gestation was generated, scaling the uterus and fetus shapes. Since fetus limbs

and organs grow at a non-linear rate and not simultaneously, these models seem unrealistic and no fetal internal organ was modeled.

Complex hybrid models using the CT images from [7], the VIP-MAN model from [13] and computer graphics models were presented in [14]. Three models were built at 3, 6, and 9 months of pregnancy. The maternal organs were highly detailed, but only fetal soft tissues and skeleton were distinguished.

In [15], a hybrid model was proposed embedding a voxelized model of a fetus (with only the brain and the eyes being detailed) and a uterus inside a voxelized woman model. As in [11], the embedding of the fetus and uterus model involved voxel editing and only the fetal brain and eyes were distinguished.

In this work, we propose to contribute to the field of pregnant-woman modeling on the following aspects:

(1) We propose to create hybrid models that include highly detailed utero-fetal units, based on segmentation results from routine US and MRI data.
(2) We propose to combine segmentations from US and MRI data to generate models at different gestational ages, including in particular 3D US segmented data from the first trimester of pregnancy, which was rarely modeled in the previous works.
(3) We propose to generate models that can be evaluated by clinical experts in terms of realism and genericness. Since maternal organs are barely and partially visible on MRI and US data, we chose, together with our clinical collaborators, to use a virtual maternal body from a synthetic woman that we fit to the partially visible external envelope of the real maternal body.

Images database

3D Ultrasound

With the collaboration of obstetricians from the hospitals of Port-Royal and Beaujon (Paris, France), we gathered 18 3D US sequences (illustrated in Fig. 1) between 8 and 14 weeks of amenorrhea (WA) with high image quality.

These US images have a sub-millimetric and isotropic resolution (typically $0.6 \times 0.6 \times 0.6\,\text{mm}^3$). The whole embryo and all the important maternal uterus tissues were visible in these images. They were acquired with the ultrasound machine VOLUSON 730 (General Electric, Milwauke, United States). We also obtained one data set, from Philips Healthcare Research acquired with the IU22 probe (Philips, Eindhoven, Netherlands).

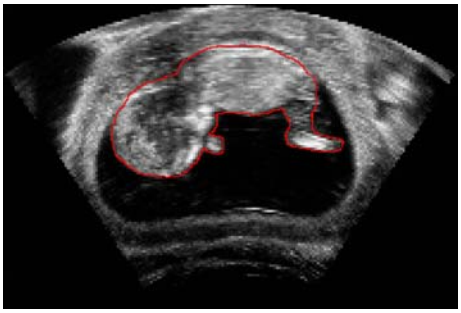

Fig. 1 Fetus outline aged of 13 W A on a US image extracted from a 3D data set

After the 18th WA, the fetus cannot be entirely captured with the ultrasound probe and we, therefore, cannot use US data after this period to model the utero-fetal unit.

Magnetic resonance imaging (MRI)

In collaboration with pediatric radiologists from the Saint Vincent de Paul hospital (Paris, France), a study [16] was performed to select the best-suited MRI imaging protocols for the segmentation of the fetus and the maternal body envelope. The quality criteria included the following: large field of view to include the whole uterus, good overall contrast, good spatial resolution ($1 \times 1 \times 4\,\text{mm}^3$), fast acquisition (less than 30 seconds), and low sensitivity to fetal movements artifacts.

The acquisition protocols Fast Imaging Employing Steady state Acquisition (FIESTA) for the General Electric systems and True Fast Imaging with Steady state Precession (FISP) for the Siemens systems were chosen, corresponding to the generic sequence Steady State Free Precession (SSFP).

During the second trimester, the gestational sac volume containing amniotic fluid is large compared with the fetus size. Hence, fetal motion artifacts are frequently observed in MRI images, preventing accurate segmentation of the fetus. We were not able to gather good-quality MRI image data for this period of gestation.

The database gathered so far contains 22 cases between 30 and 34 weeks of amenorrhea.

Methods

In this section, we detail the segmentation and reconstruction steps, which were implemented using the software tools MIPAV (http://mipav.cit.nih.gov/), Blender (http://www.blender.org), and our own 3D image-processing library.

Reconstruction from 3D US data

Regarding 3D US data, the first computational step was to segment all the uteral structures that were visible on the

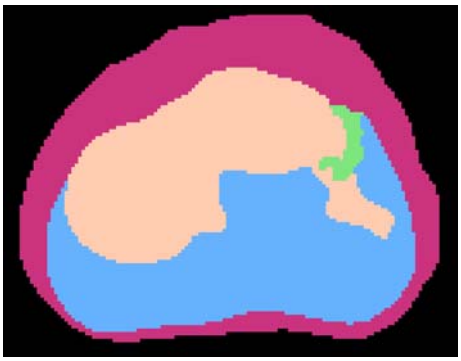

Fig. 2 Masks of an utero-fetal unit extracted from a 3D US data set with the embryo (*pink*), the trophoblast (*purple*), the amniotic fluid (*blue*), and the umbilical cord (*green*)

images. This was done either manually for a number of data sets, or automatically, using the method described in [17], where statistical distributions of tissues are integrated in a deformable model to differentiate the amniotic fluid from the fetal and maternal tissues. Depending on the gestational age, the following utero-fetal structures can be segmented on the US images: the embryo, the amniotic fluid, the umbilical cord, the trophoblast, the myometrium, the endometrium, and the yolk sac. An example of fetus segmentation on US data is shown in Fig. 1.

The volumes of interest of the different tissues were validated by an expert obstetrician and converted into labeled masks (as illustrated in Fig. 2). On each mask, triangulation was applied on the surface in order to construct the corresponding surface mesh.

Reconstruction from MRI data

For the MRI data, the segmentation procedure is based on morphological information and deformable models [18] and is performed automatically for some organs (eyes, brain …) and interactively for others, similarly to the US data. Regarding quantitative validation of the fetal anatomy, all segmentations performed to extract the fetal structures (body envelope, brain, lungs, urinary bladder, eyes …) were validated by our clinical collaborators, who provided the image data and work routinely with them to precisely measure fetal growth on individual organs.

However, due to the anisotropy of the images (the voxel size is typically $1 \times 1 \times 4\,\text{mm}^3$), staircase effects corrupt the generated surfaces of the segmented objects (as illustrated in Fig. 3), which are not compatible with dosimetry simulations.

Indeed, the numerical algorithms used to estimate the propagation of electromagnetic waves and to infer the induced absorbed dose require smooth and isotropic anatomical models. Therefore, the segmented contours are filtered to reduce these staircase effects, using a simple Gaussian filter.

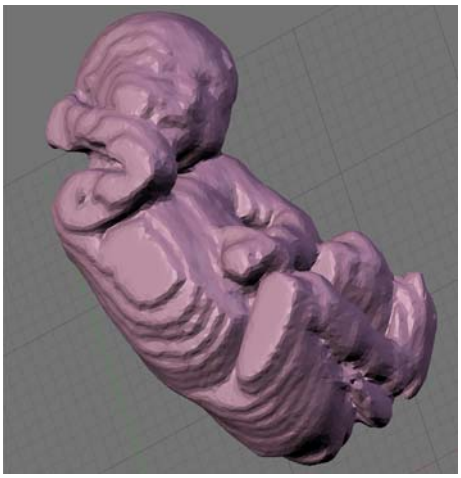

Fig. 3 A 3D fetus shape, extracted from an MRI data set, with staircase effects

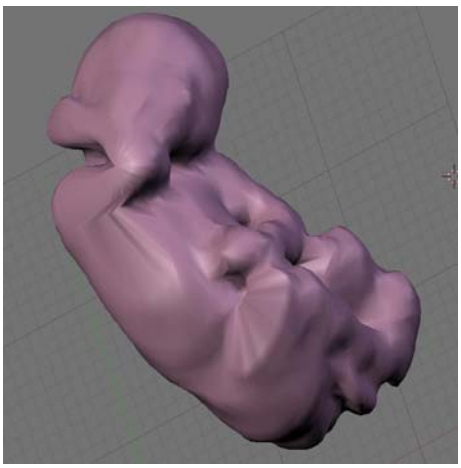

Fig. 4 A 3D fetus shape, extracted from an MRI data set, after Gaussian smoothing

Planar contours of the filtered segmented structures (illustrated in Fig. 5), extracted on the set of MRI slices, are then connected to obtain smooth triangulated meshes (as illustrated in Fig. 4). The obtained surfaces match the smoothness requirements for dosimetry computation, while keeping a good precision and accuracy with respect to the original data. In [19], we present a more sophisticated method based on computer graphics algorithms to generate smooth models.

Depending on the age of the fetus, we are able to extract the following utero-fetal structures from the MRI images: fetus envelope, eyes, brain, urinary bladder, lungs, heart, uterus, amniotic fluid, and umbilical cord (as illustrated in Fig. 6). Each tissue is characterized by a unique label in the final model. Different tissue-specific properties such as mass density or conductivity can be associated with these labels, prior to dosimetry studies, according to the recommendations

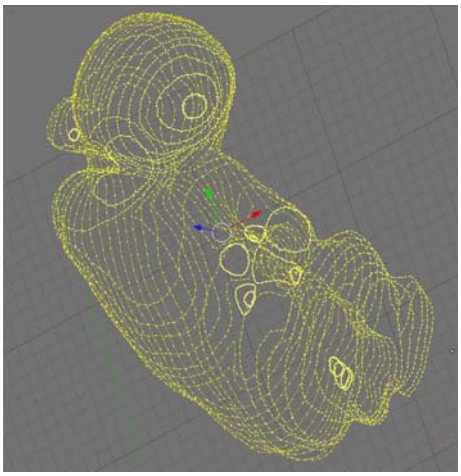

Fig. 5 Set of 2D fetus contours, extracted from an MRI data set, after Gaussian smoothing

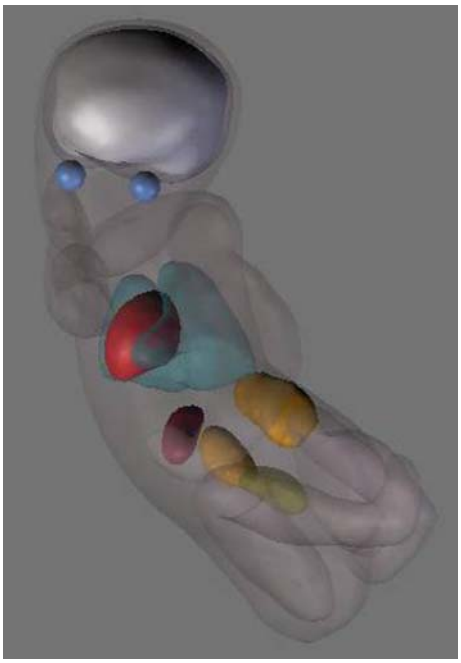

Fig. 6 Fetus envelope and internal organs extracted from an MRI data set: the transparent fetus envelope contains the brain (*gray*), the eyes (*blue*), the heart (*red*), the lungs (cyan), the stomach (*purple*), the kidneys (*orange*), and the urinary bladder (*yellow*)

of the Federal Communication Commission (http://www.fcc.gov/fcc-bin/dielec.sh).

Fetus positioning in a virtual maternal body

The field of view of the medical images used to extract the utero-fetal unit included only a part of the maternal body. In order to model a complete pregnant woman body, we use the software tool DAZ Studio that provides a virtual woman body which is easily deformable and can be placed in arbitrary posture. Recognizing the difficulty to represent the displacement of organs within the maternal body, we do not include them yet to avoid displaying false anatomical information. Thus, we simply represent the maternal model as a single homogeneous tissue. Using the software tool Blender, we then insert the fetus in the virtual maternal body (as illustrated in Fig. 7).

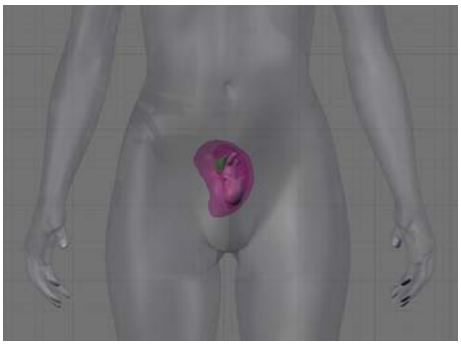

Fig. 7 3D model of a pregnant-woman with the utero-fetal unit placed inside a virtual maternal body shape

When using MRI segmentation data, we use the same virtual maternal body, reshaped using lattice-based free form deformations, to fit the actual part of the maternal envelop visible on the medical image data. The final maternal external envelope is, therefore, different for each model. Regarding the positioning of the fetus within the mother, we use all the information available from the limited field of view on MRI data and complete the positioning under the guidance of an obstetrician, who feels confident that the remaining uncertainty in the positioning process is negligible compared to the spatial and numerical resolution used in the dosimetry studies, and compared to the variability between pregnant women.

In Fig. 8, we provide a sketch of a pregnant woman body in a mid-sagittal section. According to [20], the uterus is generally located 2 cm below the subcutaneous interface of the mother and follows the shape of the spine. Half of the thickness of the non-gravid abdomen consists of the spine and major blood vessels such as the aorta. In vertex position the head of the fetus is positioned on a line (lower green line) linking the pubis and the top of the sacrum. The feet of the fetus are generally under the D10 rib (upper green line). The urinary bladder is below the uterus. When it is filled, it elevates the uterus and when it is empty, the uterus topples over it and forward.

Voxelized models

For dosimetry studies, we had to generate voxelized models. Each tissue type was assigned a unique label in order to

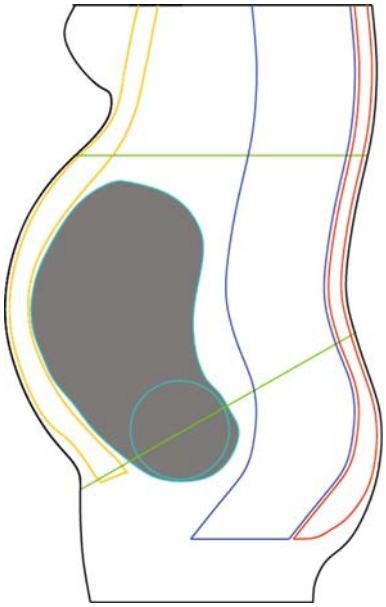

Fig. 8 Sketch of a pregnant-woman body in mid-sagittal section, including the uterus (*gray*), head of the fetus (*cyan*), subcutaneous tissues (*yellow*), spinal cord (*red*), and major vessels and spine (*blue*). Landmark lines are indicated for the head (*bottom*) and feet (*top*) of the fetus

create the final 3D images that contained all the segmented tissues (as illustrated in Fig. 9).

When we created the voxelized models, we had to handle the introduction of numerical artifacts at tissue interfaces, corresponding to anatomical incoherences such as open skulls or open uterus. To avoid such artifacts, we modified the labels of tissues that surrounded other ones as the union of the surrounding tissue and the dilation of the internal tissues. For example, we changed the uterus into the union of the uterus and the dilation of the fetus and the umbilical cord.

Results

In this study, we modeled four pregnant women with embryos segmented from 3D US images at 8, 9, 10, and 13 weeks of amenorrhea and five pregnant women with fetuses segmented from MRI images at 30, 32 (two models), 33, and 34 weeks of amenorrhea. All models were anatomically validated by obstetricians and pediatric radiographers. These models include anatomical variations to represent several typical pregnancy configurations. In particular, the set of models includes:

- a fetus in breech position (illustrated in Fig. 10). This position can have an impact on the dosimetry measures;
- a woman with filled urinary bladder (as illustrated in Fig. 11). This configuration elevates the fetus position and can also affect the dosimetry measures; and
- a model where the MRI data were acquired with the woman in a lateral decubitus position, whereas the others were acquired in dorsal decubitus positions. This position changes the shape of the maternal abdomen and also the fetus position.

The main contribution of this work relies on the fact that we provide anatomically detailed utero-fetal unit models, built from real imaging data using non-invasive 3D acquisitions. In particular, this is the first time, to our knowledge, that voxelized models of the utero-fetal unit are generated from real medical image data (here 3D ultrasound data) during the first trimester.

These models were exploited by a collaborating group for dosimetry simulations. The influence of the anatomical variability (e.g. the fetal and maternal positions, the urinary bladder filling …) on the outcome of simulated dose absorption rates will guide our future work for refining our current models and generating new ones.

Conclusion

In this paper, we have proposed a new computational framework to construct hybrid pregnant women models with detailed utero-fetal anatomy extracted from MRI and 3D US image data, combined with a synthetic model of a woman body. Our approach focuses on the computation of detailed and realistic

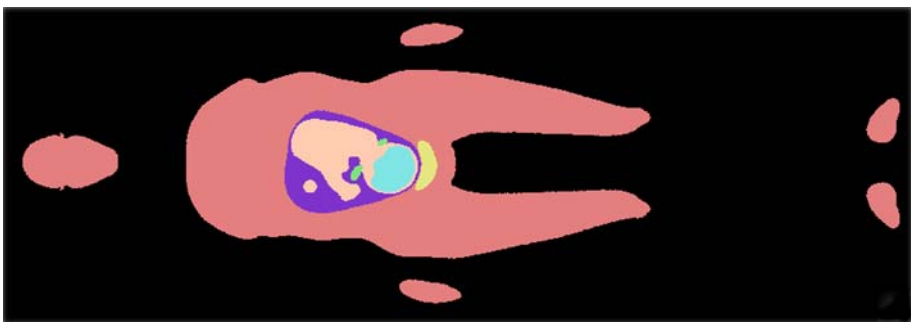

Fig. 9 Voxelized model of a pregnant woman and a fetus

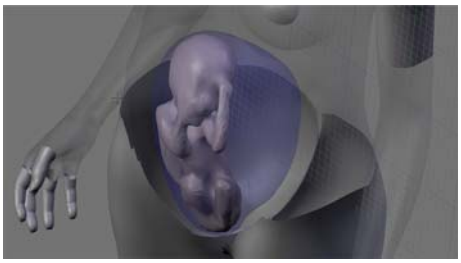

Fig. 10 A 3D model of a pregnant woman with the fetus in breach position

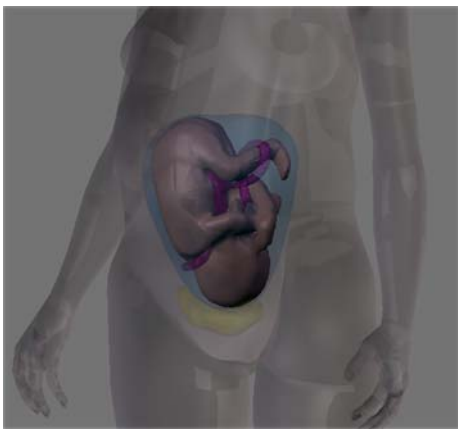

Fig. 11 A 3D model of a pregnant woman with a filled urinary bladder

utero-fetal models, based on imaging data acquired in routine clinical screening. In that respect, they appear to complement well other existing models. Methodological developments as well as manual and automated segmentation enabled us to incorporate in these models several fetal structures, including the brain, the eyes, the heart, the lungs, the urinary bladder, and other tissues such as the uterus, the amniotic fluid, the umbilical cord, the trophoblast, the myometrium, the endometrium, and the yolk sac depending on the fetus gestational age and the imaging modality. In this study, we created nine models at various stages of gestation and in different positions. As an ongoing work, we are processing additional image data sets to generate new models. Positioning of the fetus inside the synthetic woman body was performed under medical control. All models were anatomically validated by clinical experts for the shape, size, and position of each tissue and organ we have modeled. The validation of our model in terms of usability for dosimetry simulation will be detailed in a separate paper. In [21], preliminary dosimetry studies with these models are performed with encouraging results regarding the sensitivity of dosimetry measures with respect to fetal age and position. These models will be made freely available to the scientific community, in a near future.

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