Pol J Med Phys Eng. 2008;14(1):13-19.
PL ISSN 1425-4689
doi: 10.2478/v10013-008-0002-4
website: http://www.pjmpe.waw.pl

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Katja — the 24th week of virtual pregnancy for dosimetric calculations

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Virtual human models, a.k.a. voxel models, are currently the *state of the art* in radiation protection for computing organ irradiation doses without difficult or morally unfeasible experiments. They are based on medical image data of human patients and offer a realistic, three dimensional representation of human anatomy.

We present our newest voxel model Katja, a virtual woman in the 24th week of pregnancy. Katja integrates two previous voxel models, one obtained from the abdominal MRI scan of a pregnant patient and an already segmented model of a non-pregnant woman. The latter is the ICRP-AF, fitting the reference values for standard height, weight and organ masses given by the Internationals Committee of Radiological Protection (ICRP). The dataset was altered in order to fit the segmented foetus taken from the abdominal MRI scan. The resulting pregnant woman model, Katja, complies with the ICRP reference values for the adult female.

Key words: voxel models, pregnancy, organ dose simulation, ICRP-AF, ICRP reference.

Introduction

Virtual human models based on medical image data from real patients are currently the state of the art for dose calculations in radiation protection. Their realistic three-dimensional representation of human anatomy is crucial for organ dose calculations, since organ doses are not measurable. The existing group of voxel models describes several individuals of both sexes, children and even babies [4-10, 12, 16, 17].

Within this worldwide group lives the GSF voxel model family [11] containing two ICRP reference models of adult people.

The latest research focuses on the protection of unborn children, thus pregnant human phantoms become of extreme interest. Several models of pregnant females can be found in the literature, first of all the ORNL-Series of mathematical models by Stabin et al. [14] and Chen [2] presenting human anatomy by mathematical means.

The voxel models of the pregnant Naomi by Dimbylow [3] and Silvy [1] are constructed for calculations of non ionizing radiation, and RPI-3, RPI-6 and RPI-9 by Xu et al. [15] for calculations of ionizing radiation. Dimbylows model is a hybrid one, the mother is a voxel model but the foetus a mathematical phantom basing on a voxelized version of the mathematically modelled foetus of Chen.

The RPI series is based on the segmented computer tomography of a woman in her 30th week of pregnancy [13] which was edited by the means of Non uniform rational B-splines (nurbs) and inserted on the also modified model of woman.

Though in CT the bones are clearly visible, RPI-6 and RPI-9 contain also the skeleton of the foetus but no organs except the brain. The rest of the foetuses and the whole foetus of RPI-3 are assumed as being composed of soft tissue.

To understand the nature of a voxel model it is necessary to know how it is built and stored. Human phantoms are mathematically described as three dimensional matrixes of organ identification codes (numbers). The rows, columns and slices conform to the external dimension of a human, i.e. width, depth and height. A set of organ identification numbers uniquely represents an organ or tissue. With the help of this representation, it is possible to calculate organ doses from Monte Carlo photon transport simulations.

Voxel models are constructed on the basis of medical images coming either from Computer Tomography (CT) or MRI (Magnetic Resonance Imaging) of real patients. The data of those are also three dimensional matrixes but they content Hounsfield Units (CT) or grey values (MRI). Neither has unique identification of organs or tissues: the same Hounsfield unit or the same grey value may occur in different parts of the body, e.g. in heart and also muscle tissue. The process of replacing the Hounsfield units or grey values by organ identification numbers is called segmentation. This is a very time consuming and laborious process, where a lot of manual work is required.

Automatic routines are in general based on edge detection between tissues or organs. Because of the complex human anatomy, artefacts and weak to non-existing borders between organs make such algorithms of limited use. It is therefore necessary to draw many organ outlines by hand.

The resulting voxel model represents the individual whose medical data set was used. Because of limitations and regulations in radiological protection, a wider range of population has to be considered. For this purpose the ICRP reference models ICRP–AM and ICRP-AF were created from already segmented human phantoms as average people in order to represent a wide range of population. The two individuals within the GSF-family closest to the ICRP reference values were chosen for further modification. First the skeleton was adapted to match the height of the reference persons and afterwards the internal organs and tissues were adjusted to the ICRP organ masses. The male model ICRP-AM has a resolution of $2.08\times2.08\times8$ mm^3 and a height of 1.76 m and weights 73 kg. The female one ICRP-AF has a voxel resolution of $1.775\times1.775\times4.84$ mm^3, a height of 1.63 m and weight of 60 kg.

The female model was then used for further modifications. Medical datasets of pregnant women are rare and typically localized to a part of the body. Thus it was decided to combine two data sets in order to obtain a whole body model of a pregnant female.

Materials and methods

In order to modify voxel models, the in-house made software 'Volume Change' was created. It already turned out to be of use in the development process of the reference voxel model ICRP-AM and ICRP-AF.

With this tool it is possible to adjust segmented models via a graphical user interface. The organs and tissues are represented by their surface voxels in a three-dimensional view, but a two dimensional editing of the sagital, coronar and transversal slices is also available.

Different new functions were implemented, such as organ volume enlargement or reduction with respect to surrounding tissue, and movement of whole organs or only parts of them.

Skin movement is a special task because one has to consider wrinkles and underlying adipose tissue. The program applies the respective algorithms and shows the user how much surrounding tissue would be affected. The user can then accept or cancel the operation. The user has always the overview by organ volumes and by different three- or two-dimensional displays of modified organ or tissue. With the help of this software, challenging tasks like the subdivision of bones in cortex and spongiosa or movement of the abdominal wall can be also performed. In fact, the movement of the abdominal wall

Figure 1. Katja and the foetus on the left hand side, on the right the primal model ICRP-AF. Clearly visible is the shifted colon. In the pelvis of ICRP-AF is the unchanged uterus

and of the underlying muscles and vessels was the first step of the creation of our pregnant model Katja. The place for the foetus was estimated and part of the body was shifted outwards. Afterwards the transverse colon was lifted upwards, the ascending and descending colon left and right in dorsal direction. Pancreas and stomach were slightly shifted upwards. The small intestine was object to the biggest changes and found place in the pelvis and dorsal part of the model. After clearing this space within the female model the segmented foetus was inserted, plus placenta, umbilical cord, amniotic liquor and of course the enlarged uterus.

Results

The resulting model is the representation of a woman in her 24 week of pregnancy. The woman is an altered version of the ICRP-AF, the female reference model of an adult woman. All organ masses but adipose tissue, skin, urinary bladder and uterus remained the ICRP reference masses.

The woman has 153 organs and the foetus 18. The resolution of the voxel model Katja is $1.775 \times 1.775 \times 4.84\ mm^3$. To the day, this is the most segmented foetus model in the literature. Unfortunately the only bones inside the model are spine and skull because it was segmented from a MRI scan where bones are hardly visible. The segmented organs of the foetus are brain, skull, brain liquor, eyes, eye lenses, skin, soft tissue, spinal cord, lungs, liver, kidneys, heart, gall bladder and stomach. They were taken from the MRI scan as they could be seen.

Discussion

The resulting modifications are acceptable since the natural pregnancy changes are extremely variable. The resulting phantom with its altered organs was validated by an experienced gynaecologist.

The resulting model Katja is suited for transport calculation of radiation through the human body for baby health protection.

Acknowledgement

The authors want to thank Dr. Mueller-Lisse of the Department for Clinical Radiology at the University Hospital of Munich, for his advice.

References

[1] Cech R, Leitgeb N, Pediaditis M. Fetal exposure to low frequency electric and magnetic fields. Phys Med Biol. 2007; 52(4): 879-888.

[2] Chen J. Mathematical Models of the Embryo and Fetus for Use in Radiological Protection. Health Phys. 2004; 86(3): 285-295.

[3] Dimbylow P. Development of pregnant female, hybrid voxel-mathematical models and their application to the dosimetry of applied magnetic and electric fields at 50 Hz. Phys Med Biol. 2006; 51 2383-2394.

[4] Dimbylow P. Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields. Phys Med Biol. 2005; 50(6): 1047-1070.

[5] Dimbylow PJ. The development of realistic voxel phantoms for electromagnetic field dosimetry. Workshop on Voxel Phantom Development 1-7. 1996.

[6] Kramer R, Khoury HJ, Vieira JW, Loureiro EC, Lima VJ, Lima FR, Hoff G.All about FAX: a female adult voxel phantom for Monte Carlo calculations in radiation protection dosimetry. Phys Med Biol. 2004; 49: 5203-5216.

[7] Kramer R, Vieira JW, Khoury HJ, Lima FR, Fuelle D. All about MAX: a male adult voxel phantom for Monte Carlo calculations in radiation protection dosimetry. Phys Med Biol. 2003; 48: 1239-1262.

[8] Lee C, Lee C, Park S-H, Lee J-K. Development of the two Korean adult tomographic computational phantoms for organ dosimetry. Med Phys. 2006; 33(2): 380-390.

[9] Nagaoka T, Watanabe S, Sakurai K, Kunieda E, Watanabe S, Taki M, Yamanaka Y. Development of realistic high-resolution whole-body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry. Phys Med Biol. 2004; 49: 1-15.

[10] Nipper JC, Williams JL, Bolch WE. Creation of two tomographic voxel models of paediatric patients in the first year of life. Phys Med Biol. 2002; 47(11): 3143-3164.

[11] Petoussi-Henss N, Zankl M, Fill U, Regulla D. The GSF family of voxel phantoms. Phys Med Biol. 2002; 47: 89-106.

[12] Sato K, Noguchi H, Emoto Y, Koga S, Saito K. Japanese adult male voxel phantom constructed on the basis of CT images. Radiat Prot Dosim. 2007; 123: 337-344.

[13] Shi CY, Xu XG. Development of a 30-week-pregnant female tomographic model from computed tomography (CT) images for Monte Carlo organ dose calculations. Med Phys. 2004; 31(9): 2491-2497.

[14] Stabin MG, Watson E, Cristy M, Ryman JC, Eckerman KF, Davis J, Marshall D, Gehlen K. Mathematical models and specific absorbed fractions of photon energy in the nonpregnant adult female and at the end of each trimester of pregnancy. Oak Ridge (TN): Oak Ridge National Laboratory; 1995.

[15] Xu GX, Taranenko V, Zhang J, Shi C. A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females at the ends of three gestational periods – RPI-P3, -P6 and -P9, Phys Med Biol. 2007; 52: 7023-7044.

[16] Xu XG, Chao TC, Bozkurt A. VIP-MAN: An image-based whole-body adult male model constructed from color photographs of the Visible Human Project for multi-particle Monte Carlo calculations. Health Phys. 2000; 78(5): 476-486.
[17] Zubal IG, Harrell CR, Smith EO, Rattner Z, Gindi G, Hoffer PB. Computerized three-dimensional segmented human anatomy. Med Phys. 1994; 21(2): 299-302.