A CVH-based computational female pelvic phantom for radiation dosimetry simulation

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Background: Accurate voxel phantom is needed for dosimetric simulation in radiation therapy for malignant tumors in female pelvic region. However, most of the existing voxel phantoms are constructed on the basis of Caucasian or non-Chinese population. ***Materials and Methods:*** A computational framework for constructing female pelvic voxel phantom for radiation dosimetry was performed based on Chinese Visible Human (CVH) datasets. First, several organs within pelvic region were segmented from CVH datasets. Then, polygonization and voxelization were performed based on the segmented organs and a 3D computational phantom is built in the form of a set of voxel arrays. ***Results:*** The generated phantom can be converted and loaded into treatment planning system for radiation dosimetry calculation. From the observed dosimetric results of those organs and structures, we can evaluate their absorbed dose and implement some simulation studies. ***Conclusion:*** A voxel female pelvic phantom was developed from CVH datasets. It can be utilized for dosimetry evaluation and planning simulation, which would be very helpful to improve the clinical performance and reduce the radiation toxicity on organ at risk (OAR). **Iran. J. Radiat. Res., 2010; 8 (2): 87-91**

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INTRODUCTION

External-beam radiation therapy plays a vital role in treating malignant tumors in female pelvic region. Quite a few reports have documented the application of radiotherapy for cancers in the female pelvic area, such as cervical cancer, bladder cancer, rectal cancer etc (1-3). When delivering a high radiation dose to tumor volume, surrounding normal tissues are also under irradiation. Therefore, the radiation dose to organs within female pelvic region needs to be evaluated in order to reduce radiotherapy-induced complications.

Spatial dose distribution in human body depends heavily on the physical, anatomical and metabolic characteristics of the irradiated individual (4). It cannot be measured directly, but can be obtained using conversion coefficients, which convert measurable quantity into organ absorbed dose or effective dose (5, 6). According to the International Commission of Radiological Protection (ICRP), the effective dose can be computed by using reference computational phantoms. Computational phantoms are 3-D computer models of the human body to evaluate dose distributions, which are powerful and valuable tools in radiation dosimetry applications.

The first series of computational phantoms, Medical Internal Radiation Dose (MIRD), were developed at Oak Ridge National Laboratory (ORNL) (7). They are defined by means of Boolean combinations of simple geometrical forms (such as spheres, ellipsoids, cylinders, etc.). These

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kinds of phantoms were called stylized phantoms. They have been extensively used in the evaluation of organ doses in nuclear medicine and diagnostic examination. However, the mathematical equations used in the stylized phantoms have an intrinsic limitation to represent complex shapes of 3D organs. In recent years, many studies have demonstrated that voxel phantom, another kind of computational phantom, might be a more effective tool for dosimetric study. Voxel phantoms are derived from tomographic data of real individuals, such as MRI or CT. In comparison with stylized phantoms, voxel phantoms can describe human body more realistically.

However, the reference voxel phantom recommended by ICRP is largely based on the tomographic data of Caucasians. They cover only approximately 20% of world population. China has the largest population in the world, and Chinese are different from Caucasians in anatomy and body composition at some extent. It is very important for Chinese population to setup their own reference data for dosimetric calculation and radiation protection. Several techniques are employed in this study to construct the phantom based on CVH datasets [8, 9], the potential applications of the proposed phantom in radiation dosimetry are also presented.

MATERIALS AND METHODS

Phantom development

Data acquisition

Chinese Visible Human project was started in Third Military Medical University of China in October 2002. This project provides abundant anatomical information based on high resolution cross-sectional slices from cadavers. Up to now, five CVH datasets have been successfully collected, representing a diversity of Chinese population.

Among them, the first female CVH dataset includes 3,640 cross-sectional images in total. The serial sections were sampled at 0.25 mm interval for the head and at 0.50 mm interval for the other body regions. The data file of each section was 36 MB and the complete data file was 131.04 GB. 386 cryo-sectional slice images of pelvic region were selected from the first female CVH dataset and used as the data source in this study. Each slice image has a pixel-size of 3072×2048.

Image segmentation

All the slices were initially registered with an affine transformation based on the reserved fiducial markers. Then a series of organs and structures, including bone, ovary, fallopian tube, uterus, rectum, bladder, femoral head, vagina, ureter and urethra were segmented semi-automatically by experienced anatomists and radiologists. Figure1 illustrates a segmented slice of female pelvic region from CVH.

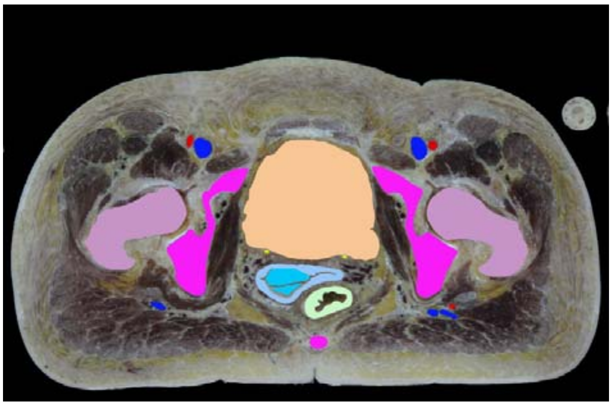

Figure 1. Segmented pelvic slice from CVH datasets.

Polygon modeling

Accurate polygon surface models of anatomical objects have a great impact in various medical applications. Usually they can be used as building blocks for computational purpose or morphometrical analysis. In our study, polygon mesh modeling was employed to construct a 3D triangular model of female pelvic region, which will be converted into voxel phantom in the following step.

Here the polygonization was done by using Amira (Visage Imaging Inc., U.S.A.), a 3D-rendering and image processing software. At first, contours of the presegmented organs and tissues in the pelvic region were obtained via interactive delineation tools within the software. Next, a set of 3D polygon surfaces of corresponding structures were generated based on those contours through built-in 3D rendering functions. Then the generated polygon models of each organ were integrated into a 3-D phantom framework and exported as *RAW* file format. Figure 2 shows the generated female polygon model.

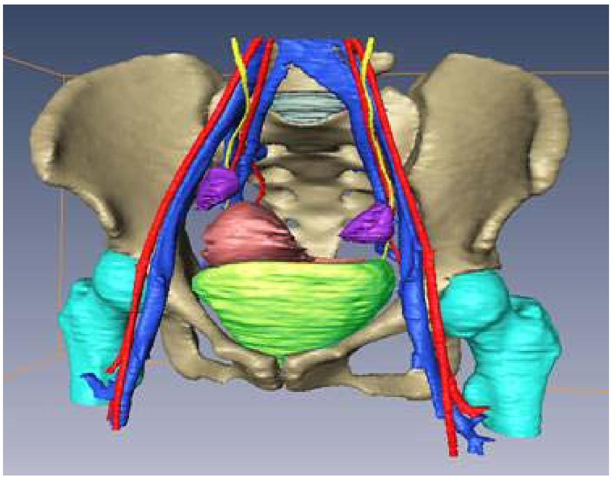

Figure 2. Polygon model of pelvic region.

Femoral head, Bladder, Bony pelvis, Vein, Artery, Uterus, Fallopian tube, Ureter

Voxelization of the pelvic polygon model

Radiation transport codes cannot fully handle polygon geometries during particle transport. To incorporate the female pelvic phantom into dosimetry calculation, the polygon geometry needs to be voxelised. The voxelization can be done by filling in the organ geometry with different ID, which is related to specific organ density. Densities of each organ and tissue required for the radiation dosimetry can be obtained from the Report 46 of the International Commission on Radiological Units and Measurements (ICRU) [10].

By specifying a set of cutting planes along the user-defined coordinate, a series of 2D transversal slices can be obtained from the generated polygon pelvic model. Organ IDs are assigned to pixels involved in certain organ by determining whether a pixel is inside or outside the organ contour within the 2D slice. If the pixel was inside the polygon, an organ ID was assigned to the pixel. When all the pixels and organs have been searched, the 2D slices were incorporated into a 3D voxel phantom with a resolution of 2mm×2mm×2mm. An in-house C++ program was developed to finish the voxelization procedure.

Dosimetry simulation

The generated phantom geometry can be loaded into software *Amide* and converted into a set of Dicom-format datasets. The generated Dicom datasets were imported into Phoenix Treatment Planning System (Phoenix TPS, Chengdu Qilin, China) followed with target definition and organ contouring. A series of radiotherapy simulations can then be performed after setting up some beam parameters by the radiation oncologists and medical physicists. To demonstrate the use of the phantom, two dosimetric studies were conducted.

Comparison studies of four-field box, 3D-CRT and IMRT

Three different radiotherapy techniques usually employed in clinical practice, i.e. four-field box, 3-dimensional conformal radiation therapy (3D-CRT) and intensity modulated radiation therapy (IMRT) were used as planning approaches for gynecological cancer based on the generated female pelvic phantom. The CTV and PTV region was defined by an experienced radiation oncologist. The prescribed dose to the PTV was 50 Gy in 2-Gy daily fractions. All plans were designed using 15-MV photons.

Four-field box plan consisted of four directions: 0°, 90°, 180°, 270°. 3D-CRT plan was configured with seven-field: 231°, 282°, 334°, 25°, 77°, 128°, and 180°. IMRT plan was also configured with seven-field: 231°, 282°, 334°, 25°, 77°, 128° and 180°.

RESULTS AND DISCUSSION

Figure 3 illustrates some simulation results from different treatment plannings. As in figure 3, we can find that IMRT techniques reduced the iradiation dose to some organs at risk (OAR), such as bladder, rectum, femoral head and ovary. Therefore it would be a comparable efficient techqiue for gynecological cancer treatment as it can be optimized to spare surrounding normal organs.

Dosimetric effects of patient rotational setup errors on IMRT

In these years, IMRT has been widely used to produce more conformal dose distribution to targets and steeper dose gradients around the target edges in radiation therapy of gynecological cancer, while rotational setup errors at each fraction of IMRT can cause dose variations within the body. Thus an unexpected underdose to a tumor and/or an overdose of radiation to adjacent normal tissues may be delivered.

The dosimetric effect of systematic rotational setup errors on treatment plan can be evaluated by simulating multiple rotational setup errors and recomputing the dose distributions in TPS. Since it is quite difficult to simulate the rotational setup errors by rotating a patient's image scans while keeping the beams static, rotational setup errors can be simulated by adjusting the gantry and horizontal couch angles alternatively[11]. The verification plans with beam-angles rotated were recomputed while keeping the same treatment parameters as for the original plan.

In our study, rotational setup errors were simulated with virtual gantry rotations of +1°, -1°, +2°, -2°, +3° and -3°, then the tumor volume coverage at 95% prescription dose level (V95) were evaluated and compared with the original plan. From the simulation results shown in table 1, we can see that systematic rotational setup errors have no large impact on the dosimetric coverage of the target volume.

Table 1. Percent change of Target volume coverage.

Rotational angle	+1°	-1°	+2°	-2°	+3°	-3°
V95 variation (%)	1.2	-0.9	1.8	-2.2	2.3	-2.5

The major goal of radiation therapy is to offer a best possible tumor control by delivering a high radiation dose to tumor volume and as low dose as possible to the surrounding normal tissues, while different tissue has different tolerance to irradiation. The organs, muscles and associated structures involved in the pelvic floor comprise one of the most complex regions of

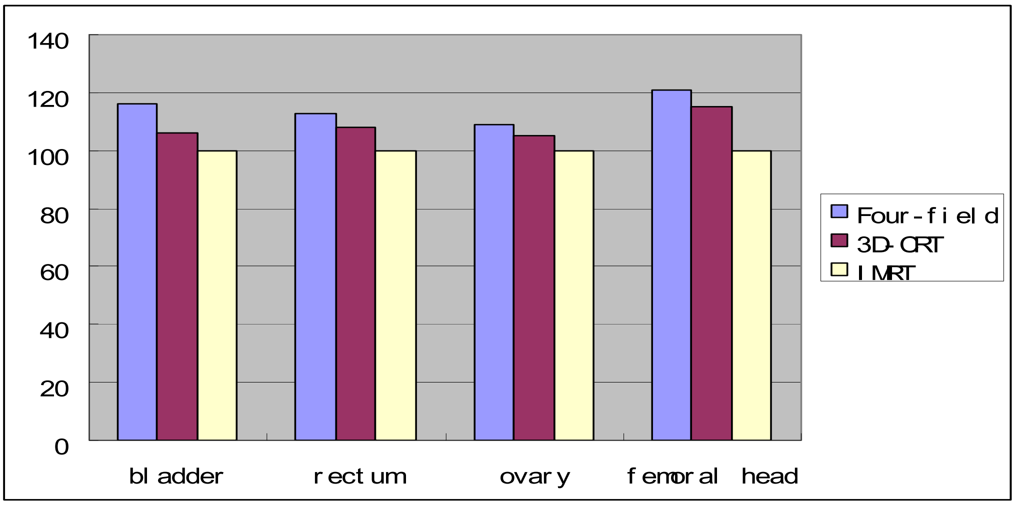

Figure 3. Relative dosimetric comparison of IMRT, 3D-CRT and four-field box for pelvic organs (Take IMRT value as 100%).

human anatomy; hence it is very difficult to distinguish several organs and structures in CT or MRI. The application of CVH datasets may provide more detailed anatomical information, which can lead to a more accurate organ segmentation of the pelvic region. With the advantages of CVH datasets, a more detailed geometry of organ and structure can be used for prediction and evaluation of dose distribution in pelvis cavity for radiation therapy.

Digital phantom as a kind of computational model has been studied for several years. Previously, most of the computational phantoms were integrated with Monte Carlo code for the purpose of radiation protection. However, it is not convenient for clinical physicists and physicians. In our study, the developed pelvic phantom was incorporated with Treatment Planning System (TPS) as an effective way of quality assurance (QA) for radiotherapy planning. Dose distributions for all the segmented structures and organs can be obtained from the TPS dose calculation, thus it would be helpful for physicians to determine the suitable dose and accordingly reduce radiation injuries to normal tissues in daily clinical QA, especially for those small structures.

The underlying methodology in this study, such as segmentation, polygonization, and phantom voxelization will be potentially useful for build whole-body computational phantom. To develop a whole-body computational phantom in the future, it is necessary to design an automatic software to speed up the procedure since the work of segmentation and polygon modeling was time-consuming. Considering the size and weight difference among people, deformable phantoms are also under development in our group to match the characteristics of individual person.

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REFERENCES

1. Mell LK, Tiryaki H, Ahn KH, Mundt AJ, Roeske JC, Aydogan B (2008) Dosimetric comparison of bone marrow -sparing intensity modulated radiation therapy versus conventional techniques for the treatment of cervical cancer. *Int J Radiat Oncol Biol Phys*, ***71:**1504-10.*
2. Fokdal L, Hoyer M, Maase H (2006) Radical radiotherapy for urinary bladder cancer: treatment outcomes. *Expert Rev Anticancer Ther, **6:** 269–279*.
3. Engels B, De Ridder M, Tournel K (2009) Preoperative helical tomotherapy and megavoltage computed tomography for rectal cancer: impact on the irradiated volume of small bowel. *Int J Radiat Oncol Biol Phys, **74** :1476-80.*
4. Park S, Lee JK, Kim JI, Lee YJ, Lim YK, Kim CS, Lee C (2006) *In -vivo* organ mass of korean adults obtained from whole-body magnetic resonance data. *Radiation Protection Dosimetry, **118:** 275–279.*
5. International Commission on Radiological Protection (1991) ICRP publication 60.
6. Choonsik L, Tomoaki N and Jai-Ki L (2006) Implementation of Japanese male and female tomographic phantoms to multi-particle Monte Carlo code for ionizing radiation dosimetry. *J Nucl Sci Technol, **43:** 937–945*.
7. Snyder WS, Ford MR, Warner G (1969) Estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom. New York: Society of Nuclear Medicine.
8. Zhang SX, Heng PA, Liu ZJ (2006) Chinese visible human project. *Clinical Anatomy, **19:** 204-215*.
9. Zhang SX, Heng PA, Liu ZJ, Tan LW, Qiu MG, Li QY, Liao RX, Li K, Cui GY, Guo YL, Yang XP, Liu GJ, Shan JL, Liu JJ, Zhang WG, Chen XH, Chen JH, Wang J, Chen W, Lu M, You J, Pang XL, Xiao H, Xie YM. (2003) Creation of the Chinese visible human data Set. *Anat Rec Part B: New Anat, **275B:** 190 –195.*
10. International Commission on Radiation Unit and Measurement (1992), ICRU Report 46.
11. Fu W, Yang Y, Li X, Heron DE, Huq MS, Yue NJ (2006) Dosimetric effects of patient rotational setup errors on prostate IMRT treatments. *Phys Med Biol, **51:** 5321–5331.*