# Anatomical Modelling of the Pregnant Radiotherapy Patient

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*Abstract*— **This study aimed to take existing anatomical models of pregnant women, currently used for radiation protection and nuclear medicine dose calculations, and adapt them for use in the calculation of fetal dose from external beam radiotherapy (EBRT). The models investigated were 'KATJA', which was provided as an MCNPX geometry file, and 'RPI-P6', which was provided in a simple, voxelized binary format. In-house code was developed, to convert both models into an `egsphant' format, suitable for use with DOSXYZnrc. The geometries and densities of the resulting phantoms were evaluated and found to accurately represent the source data. As an example of the use of the phantoms, the delivery of a cranial EBRT treatment was simulated using the BEAMnrc and DOSXYZnrc Monte Carlo codes and the likely out-of-field doses to the fetus in each model was calculated. The results of these calculations showed good agreement (within one standard deviation) between the doses calculated in KATJA and PRI-P6, despite substantial anatomical differences between the two models. For a 36 Gy prescription dose to a 233.2 cm$^3$ target in the right brain, the mean doses calculated in a region of interest covering the entire uterus were 1.0 +/- 0.6 mSv for KATJA and 1.3 +/- 0.9 mSv for RPI-P6. This work is expected to lead to more comprehensive studies of EBRT treatment plan design and its effects on fetal dose in the future.**

*Keywords*— **Radiation therapy, fetal dose, Monte Carlo dose calculation, patient protection.**

## I. Introduction

In any case where the use of external beam radiotherapy (EBRT) to treat a pregnant patient is unavoidable, it is important that the radiation dose to the developing fetus is evaluated as accurately as possible. Fetal dose estimates are needed when making treatment planning decisions, when designing personalized radiation shielding and when providing the pregnant patient with an appropriate risk assessment.

To date, estimates of fetal dose from EBRT have been made using approximate point-dose calculations or measurements in simple plastic phantoms. For example, the American Association of Physicists in Medicine (AAPM) have provided a comprehensive list of measurements of out-of-field dose from square fields in water-equivalent plastic, which can be used in estimating fetal dose from radiotherapy treatments [1]. Several phantom manufacturers have also produced anatomical models that can be augmented with bolus to obtain point dose measurements in patient-like geometries. Typical measurement geometries used for assessing fetal dose are shown in Figure 1.

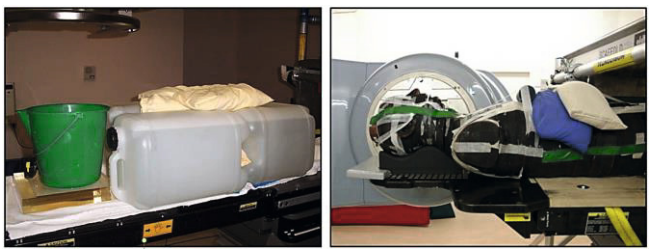

Fig. 1 Example measurement geometries for evaluating fetal dose from cranial radiotherapy.

However, the use of simplified models to acquire measurement data can lead to substantial uncertainties and the use of published out-of-field dose estimates for square fields can result in over-estimates or under-estimates of dose, when applied to more complex, irregular fields or multiple gantry orientations [2].

Calculations of out-of-field dose for pregnant patients are similarly challenging, given that radiotherapy treatment planning systems (RTPSs) are not designed or commissioned to provide accurate dose calculations more than a few centimeters beyond the field edge [3] and that, for a pregnant patient, the abdominal anatomy should be deliberately excluded (even shielded) from the planning CT [4].

While simple virtual models, similar to the physical models shown in Figure 1, can be generated using CT data or using simple geometric definitions and used to calculate out-of-field dose via Monte Carlo simulations [5], detailed anatomical models suitable for calculating fetal dose from EBRT have not previously been available.

By contrast, increasingly sophisticated models for calculating dose throughout the body have been used for radiation protection and nuclear medicine since the 1960s [6]. The Consortium of Computational Human Phantoms (CCHP) maintains a list of (currently more than 100) anatomical models of male and female adults, children and infants, including, at the time of writing, seven detailed anatomical models of pregnant women [7].



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This study, therefore, aimed to identify and access suitable radiation safety or nuclear medicine models of pregnant patients and adapt those models for use in calculating dose from EBRT treatments. This study was also extended to demonstrate the use of the resulting models to calculate fetal dose from a cranial EBRT treatment and thereby exemplify the detailed information that can be obtained from Monte Carlo calculations of out-of-field dose.

## II. Materials and Methods

### A. Patient models

Efficient and accurate Monte Carlo simulations of EBRT treatments can be completed using the National Research Council Canada's BEAMnrc and DOSXYZnrc user codes [8]. The creation of a dose calculation input file for DOSXYZnrc involves converting the patient's CT into a text file (egsphant) that lists voxel boundaries, tissues and densities [9,10,11]. In order to generate DOSXYZnrc-compatible egsphant files it was therefore desirable to use anatomical models that were available in voxelized formats.

'KATJA', from the German Research Center for Environmental Health, was based on the ICRP-AF model, and was provided in a simple, voxelised binary format [12]. 'RPI-P6', from the Rensselaer Polytechnic Institute, was based on contours of CT data and was provided as an MCNPX geometry file [13,14,15]. Both of these models provided detailed, anatomical descriptions of women at approximately the sixth month of pregnancy, but the geometries and material definitions used in the two models differed from each other, as indicated in Table 1.

Table 1 Physical characteristics of anatomical phantoms

| Feature | RPI-P6 | KATJA |
|---|---|---|
| Height | 163.5 cm | 168.4 cm |
| Weight | | 60.3 kg |
| Maximum thickness (ant-post) | 38.1 cm | 26.6 cm |
| Number of defined organs in patient | 31 | 141 |
| Number of defined organs in fetus | 3 | 21* |
| Fetal orientation | Head down, spine to ant | Head down, spine to left |
| Term | 26.5 weeks | 24 weeks |
| Number of voxels (x, y, z) | (182, 127, 545) | (299, 150, 348) |
| Voxel size (x, y, z) (mm) | (3, 3, 3) | (1.775, 1.775, 4.84) |
| Data source | Pregnant patient CT combined with VIP-Man model | Modified ICRP-AF model |
| Data type | MCNPX geo file | Binary |

* Includes umbilical cord, amniotic fluid & placenta

The RPI-P6 had been used previously to calculate radiation doses from internal nuclear medicine sources using the MCNPX Monte Carlo code [14,15], however there were major differences between the required formatting of DOSXYZnrc egsphant files [17] and the format of the RPI-P6 file. In-house code was therefore written in the C# programming language, to read in the RPI-P6 geo file and associated material densities and generate a DOSXYZnrc egsphant file for the RPI-P6 model.

The KATJA binary file was provided with a separate document listing the 162 organs used in the KATJA model, without material density information. In order to convert KATJA into a DOSXYZnrc egsphant input file it was necessary to assign densities to these 162 organs and to categorize them into no more than 9 different tissue types [17,18]. The organ density data provided with the RPI-P6 model were used to specify the densities of the organs in the KATJA model. A second in-house code was written to read the binary file and the other required information and produce a DOSXYZnrc egsphant file for the KATJA model.

When writing each egsphant, care was taken place the origin at the superior end of the phantom (useful for simulating cranial treatments), while preserving the lateral orientation of each model (heart on the left-hand side).

### B. Treatment simulation

A clinical treatment plan from a recent treatment of an oligodendroglioma of the right brain was used to demonstrate the practical use of the anatomical models produced in this study. This treatment was selected for simulation because it involved a large (approx. 6 cm diameter) brain tumor, which would pose a substantial risk to patient survival if left untreated for the term of a pregnancy [20]. The treatment plan was also identified as being suitable for hypothetical delivery to a pregnant patient, because it involved no superior-oblique (non-coplanar) beams and it consistently used a 90° collimator angle that aligned the linear accelerator's multi-leaf collimator (MLC) with the longitudinal patient direction, providing additional shielding from out-of-field dose [3,21].

The treatment was planned using the Varian Eclipse treatment planning system, for delivery via a Varian iX linear accelerator (Varian Medical Systems, Palo Alto, USA). The 233.2 $cm^3$ planning target volume (PTV) was treated to 36 Gy in 20 fractions, using five conformal photon beams with a 6 MV nominal energy.

The treatment plan was exported from the planning system as a DICOM RT PLAN object and processed using Crowe et al's MCDTK code [22,23], to produce input files

for use with our established Monte Carlo model of the Varian iX linear accelerator (linac) [16,19].

DOSXYZnrc was used to calculate the dose deposited in and around KATJA and RPI-P6 by each of the seven beams in the cranial treatment plan. In order to provide dose calculations with adequate statistical precision (0.3% in the PTV and 10% in the uterus), the irradiation of each of the two phantoms by each of the seven beams in the treatment was simulated using 2,000,000,000 particles, with each beam simulation shared across 50 of the processors of a 1924 core SGI Altix supercomputing cluster (Silicon Graphics Inc, Milpitas, USA). The total calculation time was 10,500 hours, but parallelization (mitigated by the need to share resource usage via a queuing system) meant that all DOSXYZnrc calculations were completed within 48 hours of submission.

In the 3D dose distributions produced by these simulations, the following ROIs were selected for evaluation: (a) 4 $cm^2$ areas at 5cm intervals from the anterior to the posterior side of the patient, at the level of the superior end of the uterus, (b) 4 $cm^2$ areas at 5cm intervals from the superior to the inferior end of the 'baby bump', and (c) the entire volume of the uterus. ROIs (a) and (b) were chosen to indicate some possible 'worst case scenario' doses that might be delivered to small regions of the fetal anatomy, while region (c) was used to provide an evaluation of the overall dose to the uterus, placenta and fetus, in each of the models.

This method included all sources of out-of-field dose (radiation leakage from the linac head, scatter of the primary beam from the linac head and the intervening air, and scatter of the primary beam within the patient) in the simulation.

## III. Results

### A. Model conversion

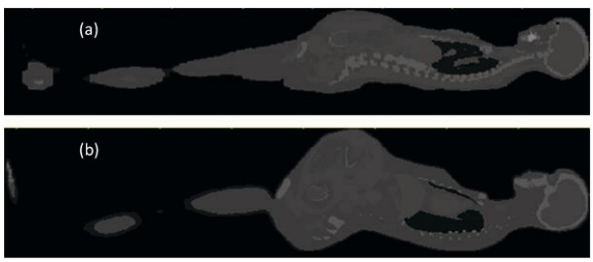


Fig. 2 Sagittal slices through (a) KATJA and (b) RPI-P6, shown as greyscale density maps (lighter grey represents higher densities and darker grey represents lower density).

The two C# phantom model conversion codes required for this work produced faithful egsphant versions of the KATJA and RPI-P6 anatomical models. Figures 2(a) and (b) show greyscale renderings of the egsphant files produced for KATJA and RPI-P6, respectively. The heights, thicknesses and total masses of the phantoms matched the values listed in Table 1 and the densities of the organs defined in the phantoms matched their assigned values.

### B. Treatment dose

The simulated irradiation of each of the two phantoms by the five-field, 36 Gy, oligodendroglioma treatment produced the ROI doses shown in Figure 3. Most mean ROI doses calculated in RPI-P6 are higher than the ROI doses calculated in KATJA, especially at the superior end of the uterus, due to the increased prominence of RPI-P6's baby bump and its consequent closer proximity to the photon source. However, these results show good agreement (within one standard deviation) between the doses calculated in KATJA and the doses calculated in RPI-P6, despite substantial anatomical differences. This suggests that anatomical variation does not negate the usefulness of the models: Figure 3 may be regarded as providing an indication of the fetal doses to be expected if a pregnant patient with a similar height and build to KATJA and RPI-P6 received the oligodendroglioma treatment used in this study.

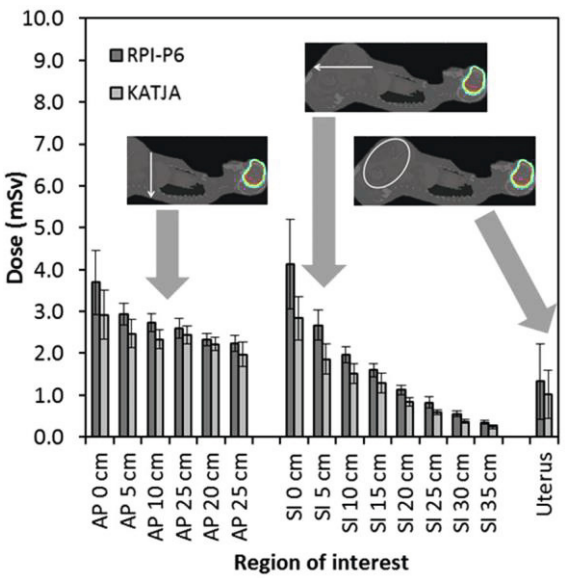


Fig. 3 Mean simulated doses in the ROIs listed in Section II.B, for the PRI-P6 and KATJA patient models (error bars represent +/- 1SD).

While most of the doses shown in Figure 3 exceed the 1 mSv annual dose limit recommended for the general public [24], they are nonetheless relatively low, around 50 times lower than the maximum leakage dose permitted 100 cm

from the photon source in a medical linear accelerator [25] and 10,000 times lower than the dose delivered to the PTV.

## IV. Conclusions

This study has demonstrated that anatomical models designed for radiation safety and nuclear medicine dose calculations can be successfully adapted for use in EBRT out-of-field dose calculation and that the results of such calculations may be relatively insensitive to anatomical variation. This work is expected to lead to more comprehensive studies of EBRT treatment plan design and its effects on fetal dose in the future. The novel codes developed for this study may be used to produce Monte Carlo simulation files from other radiation safety models, including pediatric patients of various ages.

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## Conflict of Interest

The authors declare that they have no conflict of interest.

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