

Monte Carlo Study of Fetal Dosimetry Parameters for 6 MV Photon Beam

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ABSTRACT

Because of the adverse effects of ionizing radiation on fetuses, prior to radiotherapy of pregnant patients, fetal dose should be estimated. Fetal dose has been studied by several authors in different depths in phantoms with various abdomen thicknesses (ATs). In this study, the effect of maternal AT and depth in fetal dosimetry was investigated, using peripheral dose (PD) distribution evaluations. A BEAMnrc model of Oncor linac using out of beam components was used for dose calculations in out of field border. A 6 MV photon beam was used to irradiate a chest phantom. Measurements were done using EBT2 radiochromic film in a RW3 phantom as abdomen. The followings were measured for different ATs: Depth PD profiles at two distances from the field's edge, and in-plane PD profiles at two depths. The results of this study show that PD is depth dependent near the field's edge. The increase in AT does not change PD depth of maximum and its distribution as a function of distance from the field's edge. It is concluded that estimating the maximum fetal dose, using a flat phantom, i.e., without taking into account the AT, is possible. Furthermore, an in-plane profile measured at any depth can represent the dose variation as a function of distance. However, in order to estimate the maximum PD the depth of D_{\max} in out of field should be used for in-plane profile measurement.

Key words: Fetal dosimetry, Monte Carlo, peripheral dose, radiotherapy

INTRODUCTION

Radiotherapy in pregnant patients should be aimed at controlling the patient's disease while also affording the fetus the best chance for normal life. This is a consequence of the adverse effects of radiotherapy on embryos and fetuses, which include lethality, malformations, mental retardation, growth retardation, carcinogenesis, and genetic abnormalities.^[1] Therefore, the treatment volume in a pregnant patient should never contain the abdomen. However, the dose absorbed outside of the radiation treatment field, also called the peripheral dose (PD), is responsible for fetal irradiation. The PD is produced by photons originating from treatment head and irradiated volume. The dependency of fetal dose to distance from the field's edge and field size is well known.^[1]

As recommended by American Association of Physicists in Medicine (AAPM) TG36, fetus dose should be estimated before radiotherapy to achieve the optimum balance between the risk and benefit of radiotherapy.^[1] Fetal dose estimation has been studied by several authors.^[2-9] Most of the available information has been reported for specific

patients measured either at the patient's surface or using phantoms simulating the patient, at points corresponding to the fetal's position and depth.

The variety in the reported measurement depths is due to different pregnancy stages. In several studies, the depth of fetal in different pregnancy stages has been reported using sonographic examinations. Osie and Faulkner have shown that mean fetal depth observed for all bladder volumes, fetal presentations and placenta locations increases from 6.5 ± 0.5 cm to 10.2 ± 0.7 cm over the duration of pregnancy.^[10] In another study, it has been reported that fetal depth, normalized to maternal anterior-posterior thickness, was independent or nearly independent of maternal parameters and fetal presentation ($0.3 +$ a standard deviation of 0.06, independent of gestational age).^[11] In the same study, it was also reported that, the mid-fetal to skin distances vary from approximately 6 cm at 7 weeks to 8.4 cm at 38 weeks. In another sonographic study, the data show a surprising uniformity in minimum fetal depths during the second and third trimesters.^[12] However, considering the facts that in radiotherapy fetus is located in out of field and that PD is independent of depth, as reported by TG36, any

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depth may be selected for fetal dose estimation.^[1] In spite of these data, a depth of 10 cm has been used frequently as the reference depth for fetal dosimetry.^[1,3,8] A question that has not been addressed in the literature is that if the increase in maternal anterior-posterior abdomen thickness (AT) should be considered when setting the reference depth? As pregnancy advances, the abdomen surface displaces towards the treatment head and reduces source to abdomen surface distance. Therefore, the complexity of measurement depth selection for fetal dosimetry increases when considering increased abdominal thickness (ATI).

The aim of the present study was to evaluate the effect of ATI on the dose distribution in fetus by Monte Carlo simulations and measurement. For this reason, PD depth dose distributions at different distances from the edge of the field and in-plane PD profiles (along the patient's longitudinal axis) at different depths were calculated and measured for different ATs.

MATERIALS AND METHODS

Monte Carlo Modeling of Oncor Linear Accelerator

A detailed model of Siemens Oncor linac was used for simulation of a 6 MV photon beam by BEAMnrc/EGSnrc Monte Carlo calculations^[13] and using manufacturer provided information. For out of field dose calculations, the model included the beam-line components such as target, flattening filter and also structures that affect the head leakage and collimator scatter such as primary collimator, Y jaws and multi-leaf collimators (MLC). In order to model the out of field structures, all MLC leaf pairs outside the field were assumed to be closed and interleaf gap transmission was ignored. Technical drawings were used for simulation. The initial assumption for parameters of the primary electron beam that may influence the dose profiles were done according to the nominal data.

Dose distributions were calculated by DOSXYZnrc/EGSnrc^[14] in water phantom using the scored phase space data obtained from BEAMnrc. The phantom geometries were defined as follows: The x-axis was in the cross-plane direction, the y-axis was in the in-plane direction (gun-target), and the z-axis was in the beam (depth) direction. A $100 \times 100 \times 50$ cm³ water phantom was used to incorporate enough backscatter material from the bottom and walls of the phantom. The size of the phantom's voxels (xyz), were defined depending on the required spatial resolution for model commissioning and other out of field calculations. For model commissioning these values were defined as follows: For the depth-dose calculations along the central axis, varied between $2.0 \times 2.0 \times 0.2$ cm³ (in the build-up region) and $2.0 \times 2.0 \times 0.5$ cm³ and for the profile calculations between $0.1 \times 2.0 \times 0.5$ cm³ (in the penumbra

region) and $1.0 \times 2.0 \times 0.5$ cm³. Because of the relatively small dose gradient in the out of field region,^[15] to achieve statistically acceptable results from dose calculation in this region, larger voxels were selected. The voxel dimensions were $5.0 \times 1.0 \times 1.0$ cm³ for both depth and in-plane profile calculations. By repeating the calculations using smaller voxel size the acceptability of these large voxels was confirmed.

Tuning procedure was performed with respect to the effective parameters. The physical parameters of the original electron beam that may influence the dose profile and central-axis percent depth dose (PDD) curve are beam energy, beam spot size and distance from the source.^[16,17] The off-axis factors are found to be very sensitive to the mean energy of the electron beam, the full width at half maximum (FWHM) of its intensity distribution, its angle of incidence, the dimensions of the upper opening of the primary collimator, the material of the flattening filter and its density.^[17] No energy spread for electron beam was considered because this parameter has shown no considerable influence on beam profile or depth dose curves.^[18,19] The mean energy and the FWHM of the incident electron beam intensity distributions are derived by matching calculated percentage depth-dose curves and off-axis factors with measured data. The central axis depth dose distributions and lateral dose distributions at depth of 10 cm for of 10×10 cm² and 40×40 cm² field sizes were calculated in water phantom. These profiles are represented as an appropriate agent for model commissioning.^[20] The EGSnrc utility program STATDOSE^[21] was used to extract dose profiles from the dose distributions generated by DOSXYZnrc.

Measurements to verify the accuracy of the Monte Carlo were made with an automatic water phantom (Medphysto mc2, mp3, PTW, Germany) and two 0.12 cm³ PTW ionization chambers one as reference and the other as dose chamber ($N_{D,w} = 5.31$ cGy/nC). The phantom was set to 100 cm source to surface distance (SSD) and was irradiated using 10×10 cm² and 40×40 cm² fields. The measurements were performed with 2 mm resolution for both PDD curves and beam profiles.

Monte Carlo Calculation of Out of Field Dose

Additional Monte Carlo calculations were done to obtain information about the ATI effect on out of field dose distributions, using the commissioned head model. The simulated phantom was divided into two segments, one considered as chest and the other as abdomen. The ATI with progress of pregnancy was simulated using three 5 cm RW3 slabs steps. Therefore, ATI = 0 and ATI = 5 correspond to the abdomen phantom surface at the same level and 5 cm above the chest phantom surface, respectively. SSD for the chest phantom remains constant in all cases. The illustration of phantom with 5 cm increased AT is shown in

Figure 1. The irradiation conditions were as follows: 6 MV $10 \times 10 \text{ cm}^2$ field incidents on the chest section of phantom at fixed SSD of 100 cm. The distance between the edge of the field and superior border of the abdomen was 3 cm.

For different ATIs, depth dose profiles were calculated at 5 and 15 cm distances from the edge of the field. In-plane dose profiles were calculated at 10 cm depth. Additionally, two in-plane dose profiles were calculated at 10 and 25 cm depths in the phantom with $\text{ATI} = 15 \text{ cm}$.

Out of Field Measurements

PD values range between 5% and 50% of maximum dose along the central axis.^[22] Also, the particles responsible for PD show a wide energy spectrum. Therefore, it is necessary to use an energy independent dosimeter with high dynamic range and sensitivity for out of field dosimetry. Radiochromic film provides all the above mentioned requirements.^[23] In this study, GafChromic, EBT2, radiochromic films (International Specialty Products, Inc., Wayne, NJ, USA) were used. The film calibration was performed according to Devic procedure.^[24] The film was cut into rectangular pieces of approximately $25 \times 3 \text{ cm}^2$, and marked to keep track of the orientation of the film. The films were scanned at a resolution of 127 dpi (0.2 mm/pixel) using a Microtek scanner. An in-house MATLAB routine was used for image processing. The processing contains extraction of the red component of the RGB scanned images and subsequently determination of the net optical density.

PD measurements were done in RW3 slab phantom using radiochromic films. The slabs were served as abdomen phantom attached to an inhomogeneous head and chest phantom. For measurement of depth and in-plane dose profiles, slabs were positioned vertically and horizontally respectively. The half body phantom was irradiated at $\text{SSD} = 100 \text{ cm}$ using a 6 MV, $10 \times 10 \text{ cm}^2$ photon field, while 3 cm distance was considered between the border of field and superior border of abdomen phantom. The delivered dose to depth of maximum dose at central axis, in all the cases was 50 Gy. Proper thickness of slab phantoms was added to the abdominal phantom in order to create different ATIs. Depth dose profiles were obtained at 5 and 15 cm distances from the edge of the field for different ATIs. In-plane dose profiles were measured at 5 and 10 cm depths in flat abdomen phantom.

Dose measurements with radiochromic film include two sources of uncertainties, those directed by the experimental measurement and the uncertainty introduced by the calibration curve fit procedure. The uncertainty due to measurements is limited by the followings: The overall uncertainty of the reference dose measurement in the phantom, the uncertainty due to non-uniform thickness of the sensitive layer and uncertainties associated with the densitometer used to

measure the optical density.^[25] When using Devic protocol for film dosimetry using EBT model GafChromic films, for an uniform field of above 0.4 Gy, the overall one-sigma dose measurement uncertainty is up to 2%.^[24] The dose values measured in this study were more than 0.4 Gy.

RESULTS AND DISCUSSION

We developed and validated a Monte Carlo model of Siemens Oncor accelerator for simulating PD of 6 MV photon beam.^[26] The results of simulated and measured PD as a function of distance from the central axis in the in-plane direction are illustrated in Figure 2. The results were normalized to the maximum dose along the beam's central axis. Model beam commissioning was performed using different acceptance criteria for following regions: Umbra, penumbra, and out of field. Local difference percentage values ((Calculation-Measurement) $\times 100$ /Measurement) of 2% for umbra, 30% for out of field region and 10% for penumbra region were used. For penumbra region, a distance to agreement of

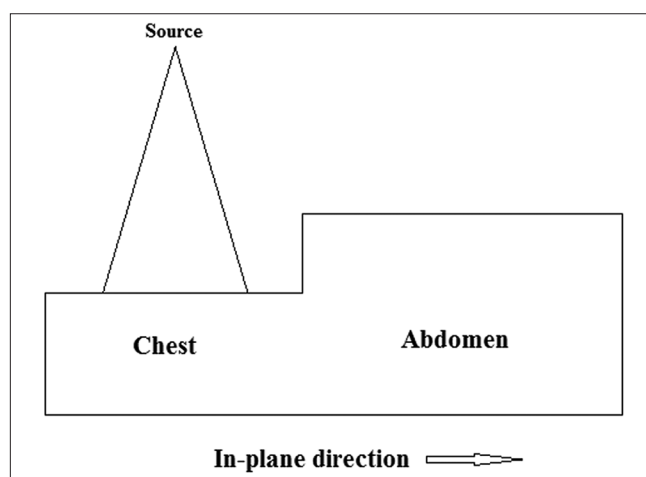


Figure 1: A diagram of the irradiated phantom with increased abdomen thickness ($\text{ATI} = 5 \text{ cm}$)

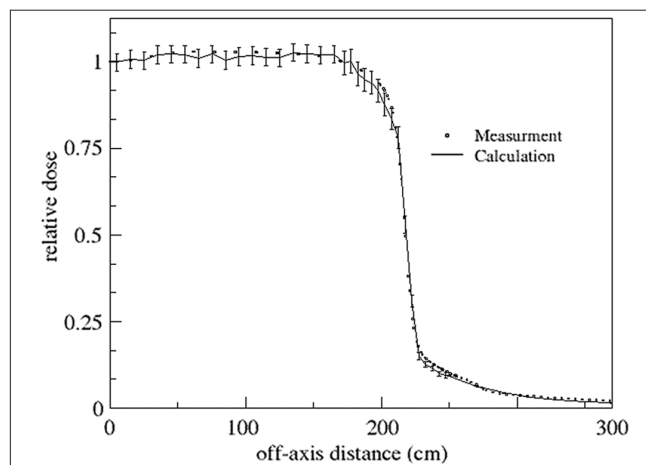


Figure 2: Measured and calculated in-plane profiles of a 6 MV photon beam in and out of a $40 \times 40 \text{ cm}^2$ field^[25]

2 mm was used as well.^[27] The difference percentage values calculated in this study for umbra, penumbra, and out of field are 1.04%, 7.5%, and 17%, respectively. The distance to agreement in penumbra is less than 2 mm. The maximum statistical uncertainty in umbra, penumbra, and out of field are 3.5%, 4%, and 9%, respectively.

The mean energy and the FWHM of the incident electron beam intensity distributions were tuned by comparing the calculated depth dose curves and off-axis factors with measured data. For 6 MV photon beam, a Gaussian spatial spread (3 and 2 mm in x and y directions, respectively) and a mean energy of 6.7 MeV were obtained for electron beam.

Figure 3 illustrates the PDD distributions, measured and calculated at three distances from the central axis, i.e., 7.5, 10.5, and 15.5 cm in the in-plane direction. These data correspond to the abdomen phantom, with its surface at the same level as the chest phantom, i.e., ATI = 0 (a flat phantom). It is clear from this figure that the PD is approximately depth independent, except for an increase near the surface at all distances from the field edge and another increase in depth close to the field border. The second increase occurs after a minimum that takes place at shallow depths. The surface dose in out of field is the result of electrons emanating from the accelerator and the air gap between the accelerator head and phantom.^[15,28] By termination of the range of these electrons, dose reduction occurs. Primary beam divergence in addition to dominant contribution of internal scatter in PD in near distance from the field edge is likely the reasons of the second increase in depth dose. Unlike our research, in Key's study of PD for a Varian accelerator, the surface dose at different distances was almost double the dose at any other depth.^[15] The dissimilar out of beam structures in two model of accelerator can be the reason for this difference.

In order to analyze the effect of ATI on PDD, the results of measured and calculated PDDs at two distances of 5 and 20 cm from the edge of the field with different ATs are shown in Figures 4 and 5. When AT increases, the abdomen surface gets closer to the treatment head and the reference depth of measurement occurs in a different location with reference to the treatment surface. However, at points near the field's edge, where internal scatter is the main source for PD,^[1,29,30] depth profiles show a shift to the depth by a distance equal to ATI [Figure 4]. This means that an increase in AT dose not have any effect on internal scatter, and hence on PD. On the contrary, at further points, where the head leakage is the main source for PD,^[1,29,30] increase in AT will cause a decrease in PD [Figure 5]. At all distances, the dose to surface of the abdomen decreased by increase in AT.

Figure 6 shows the in-plane PD profiles calculated at two depths of 5 and 10 cm for ATI = 0. This figure demonstrates that the PD variation as a function of distance from

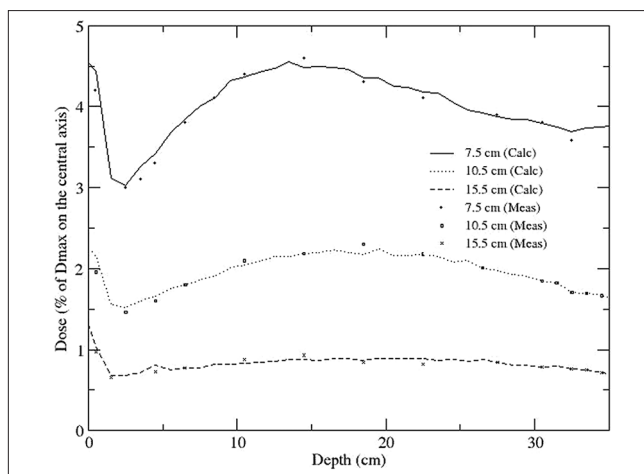


Figure 3: Peripheral dose depth profiles from a 10×10 cm² field. Measured (Meas) and calculated (Calc) data were obtained at 7.5, 10.5, and 15.5 cm from the central axis in the in-plane direction in flat abdomen phantom

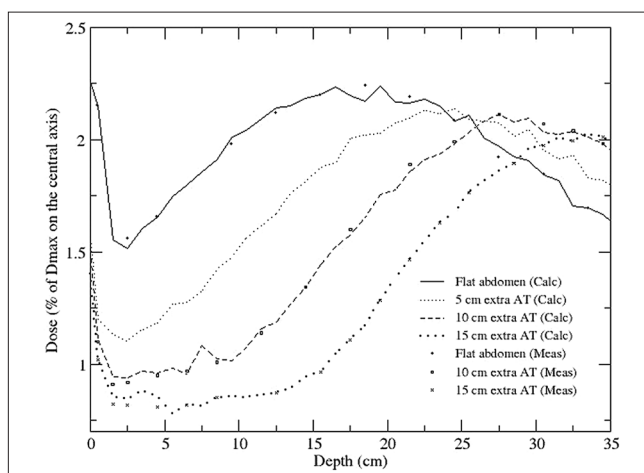


Figure 4: Measured and calculated depth profiles at 5 cm distance from the edges of a 10×10 cm² field using different abdomen thicknesses

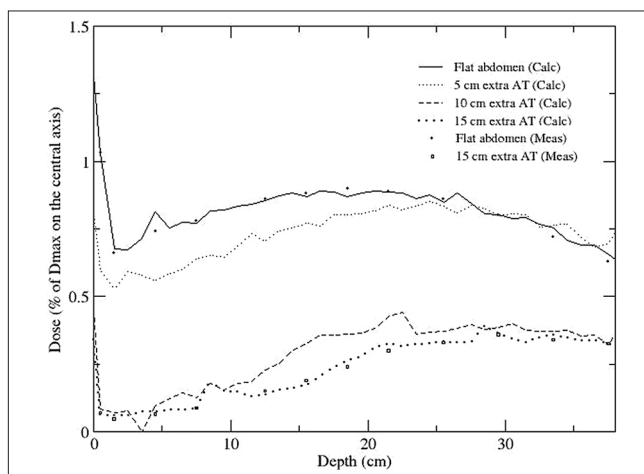


Figure 5: Measured and calculated depth profiles at 20 cm distance from the edges of a 10×10 cm² field using different abdomen thicknesses

the field limit is independent of depth but dose values increase with depth.

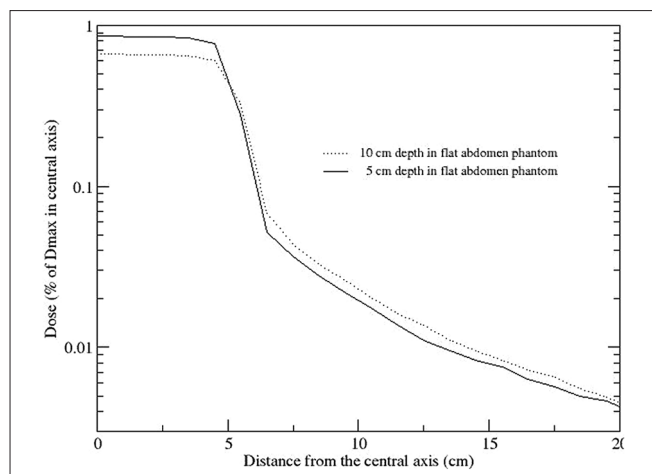


Figure 6: In-plane peripheral dose profiles calculated at depths 5 and 10 cm in flat abdomen phantom

In Figure 7, the simulated and measured in-plane PD profiles that were obtained for different ATI are presented. The considered axis was located at 10 cm depth in flat phantom (ATI = 0) and 5, 10, and 15 cm in protuberant abdomen phantoms. All results were normalized to the maximum dose along the central axis. This Figure 7 presents that the ATI does not have a considerable affect on either the dose values or dose variation as a function of distance from the central axis. By an increase in AT, the dose produced by leakage and collimator scatter reduces due to increased attenuation. This deficit, however, is compensated by increase in secondary particle production in increased abdomen thickness.

CONCLUSION

In this study, we have evaluated the fetal dosimetry parameters using a verified Monte Carlo model of a 6 MV photon beam from a Siemens Oncor linear accelerator. A satisfactory agreement between calculated doses with measured data was found. The dependency of fetal dose to distance from the field's edge is already known and the stage of pregnancy is usually considered when selecting a reference distance for fetal dosimetry. This model was used to evaluate the effect of depth, and abdominal thickness in fetal dosimetry. It has been reported that dose in out of field is independent of depth and PD can be measured at one reference depth.^[1] The results of this study show that a minute variation of PD with depth exists at shallow depths and distances near the field's edge. In our study, at distances near the field edge, a high surface dose having about the same value as the maximum dose at depth was followed by a minimum.

The increase in AT did not show any effect on the PD distribution as a function of distance from the field's edge. However, by increasing the abdomen thickness, the peak of depth profiles is shifted to larger depths in the abdomen. Despite this shift, depth of maximum PD remains

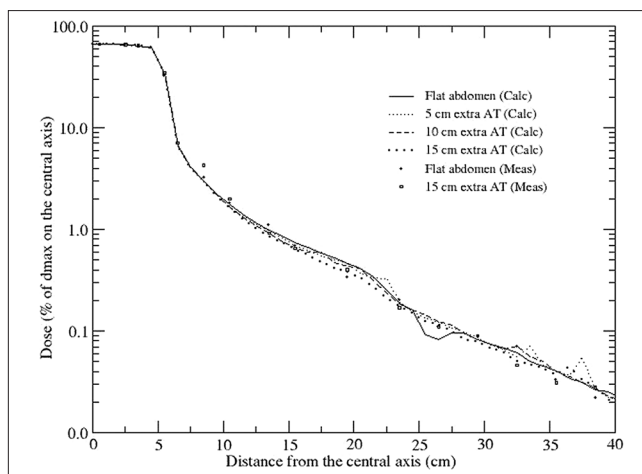


Figure 7: Measured and calculated in-plane peripheral dose profiles along the same axis in 0, 5, 10, and 15 cm extra abdomen thickness phantoms

unchanged with respect to the treatment surface. Thus, it is concluded that estimating the maximum fetal dose, using a flat phantom, i.e., without taking into account the abdomen thickness, is possible. The results of this study show that, an in-plane profile measured at any depth can represent the dose variation as a function of distance. However, in order to estimate the maximum PD, the depth of D_{\max} in out of field should be used for in-plane profile measurement.

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BIOGRAPHIES



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