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Monte Carlo simulation of the transit dosimetric response of an \( \alpha \)-Si electronic portal imaging device

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Abstract.

Amorphous silicon (\( \alpha \)-Si) electronic portal imaging devices (EPIDs) are x-ray detectors frequently used in radiotherapy imaging and dosimetry applications. EPIDs employ a copper plate and gadolinium oxysulfide phosphor screen with an array of \( \alpha \)-Si photodiodes to indirectly detect incident radiation. In this study, a previously developed Monte Carlo (MC) model of an \( \alpha \)-Si EPID has been extended for transit dosimetry. The \textsc{Geant4} MC toolkit was used to integrate an \( \alpha \)-Si EPID model with two phantoms and a 6 MV x-ray source. A solid water phantom was used to simulate EPID transmission factors, field size output factors and relative dose profiles and results were compared to experimental measurements. An anthropomorphic head phantom was used to qualitatively compare simulated and measured portal images of humanoid anatomy. Calculated transmission factors and field size output factors agreed to within 2.0% and 1.9% of experimental measurements, respectively. A comparison of calculated and measured relative dose profiles yielded >98% of points passing a gamma analysis with 3%/3 mm criterion for all field sizes. The simulated anthropomorphic head phantom image shows macroscopic anatomical features and qualitatively agrees with the measured image. Results validate the suitability of the MC model for predicting EPID response in transit dosimetry.

1. Introduction

Amorphous silicon (\( \alpha \)-Si) electronic portal imaging devices (EPIDs) serve a number of important clinical applications in modern radiotherapy. EPIDs are routinely used to image patient anatomy and verify patient setup prior to treatment. EPIDs are also suitable dosimeters since the pixel values of acquired images correlate to the absorbed dose in the detector. One method of performing dose verification using EPIDs is therefore by comparing portal dose images to
dose distributions predicted using an EPID model. EPID dosimetric characteristics and their various clinical uses for dosimetry have been reviewed by van Elmpet et al.\[1\]

A number of arguments support the integration of EPID dosimetry into routine clinical practice. Linear accelerator (linac) vendors typically supply a-Si EPIDs with the necessary hardware mounted directly to the gantry, in line with the megavoltage (MV) treatment x-ray source. This configuration provides a readily available mechanism to detect the MV beam and enables direct monitoring of both patient position and dose delivery from the beam’s-eye view. When compared to alternative 2D dosimeters such as arrays of diodes or ion chambers, a-Si EPIDs offer increased spatial resolution (typically 0.4×0.4 mm²) and real-time data acquisition capabilities. Additionally, EPIDs are resilient to radiation-induced damage and respond both linearly with dose and independently of dose rate\[2, 3\]. One centre has reported on the routine use of EPIDs for pre-treatment and in vivo dosimetry, including the EPIDs ability to detect errors in treatment delivery\[4\].

The goal of this study is to extend the functionality of an EPID model that we previously developed for non-transit dosimetry\[5\] by integrating phantom geometries into the model. In doing so, we may investigate the EPID response in a transit dosimetry configuration that is more representative of clinical treatment situations. Furthermore, we aim to validate the transit dosimetric response of this model against experimental measurements.

2. Monte Carlo model and detector geometry
2.1. 6 MV photon source
The MC radiation transport code EGSnrc\[6\] (V4 2.3.1) with user code BEAMnrc\[7\] (V4 2.3.1) were used to create a 6 MV photon source model of an Elekta Synergy linac (Elekta, Crawley, UK). A description and validation of the source model has been previously reported\[5\]. The simulation of 10⁹ primary histories was performed to generate phase space files for square fields ranging in size from 2×2 to 9×9 cm² (defined at the isocentre, 100 cm from the target).

2.2. EPID geometry and physics processes
The GEANT4 MC simulation toolkit\[8\] (version 9.4) was previously used to develop a model of an a-Si EPID and validate its dosimetric response in a non-transit configuration\[5\]. A complete description of the EPID geometry may be found in the previous study as only a brief overview is given here.

The EPID model (Figure 1) consists of a series of uniform slab layers with geometries and material compositions based on specifications provided by the manufacturer of a research EPID (XRD 1640 AN CS) used in the validation stage of this study (PerkinElmer, Santa Clara, CA). The EPID model has a cross-sectional area of 41×41 cm² and was positioned at a source to detector distance (SDD) of 160 cm for all simulations. It incorporates a 1 mm Cu buildup layer, a 133 mg cm⁻² Gd₂O₂S:Tb phosphor screen (Lanex Fast Back, Carestream Health, Inc. Rochester, USA) and a 0.1 mm thick layer of a-Si supported by a 1 mm SiO₂ substrate.

The standard GEANT4 electromagnetic physics models were used to simulate radiation transport within the MC model. The transport of optical photons originating in the phosphor screen was not explicitly simulated. We previously found that optical transport does not significantly change calculated dosimetric quantities relative to those calculated using only standard electromagnetic physics\[5\]. Simulated processes included Compton scattering, pair production, photoelectric absorption, impact ionization, Bremsstrahlung radiation, electron/positron annihilation and multiple scattering.

2.3. Phantom definitions
This study incorporated two distinct phantom geometries into the MC model to investigate separate EPID dosimetric characteristics. The first phantom was a simple homogeneous box of
solid water with a cross-sectional area of $40 \times 40 \text{ cm}^2$ and a thickness along the central axis that varied depending on the quantity being simulated. The second phantom was an anthropomorphic head that was defined by integrating a set of CT images into the MC model using functions distributed with the GEANT4 source code. Both phantoms were centred about the isocentre and the head phantom was oriented with its anterior-posterior (AP) axis aligned with the beam central axis.

Figure 1. Schematic of the model components. An x-ray track incident from the left Compton scatters first in the phantom and then in the copper, creating an electron track that deposits energy in the phosphor.

3. Simulated dosimetric quantities

The EPID dose response characteristics investigated in this study include transmission factors, field size output factors and relative beam profiles. An image of an anthropomorphic head phantom was also simulated for qualitative evaluation. All quantities were calculated by tracking particles from the source phase space files and scoring the energy deposited in the phosphor layer of the EPID in a 2D histogram. Each histogram contained $1024 \times 1024$ bins ($0.4 \times 0.4 \text{ mm}^2$ pixels), equal in number and size to the pixels of the research EPID. All MC simulations were performed using a computer cluster of 252 2.67 GHz CPUs and the open source message passing interface OpenMPI (www.open-mpi.org) was used to facilitate parallel processing. ROOT[9] (version 5.28.00) was used for all post-processing analysis.

3.1. Transmission factors

Transmission factors were calculated by varying the solid water phantom thickness from 0 to 40 cm in 10 cm increments with a fixed beam field size of $9 \times 9 \text{ cm}^2$. The mean response within the central $1 \times 1 \text{ cm}^2$ region of each 2D histogram was calculated, normalized to the response for the phantom thickness of 0 cm. Uncertainties in all output factor calculations are quoted as the standard deviation of the response within the central region.

3.2. Field size output factors and relative dose profiles

Field size output factors and relative dose profiles were calculated by varying the beam field size from $2 \times 2$ to $9 \times 9 \text{ cm}^2$ with a fixed solid water phantom thickness of 20 cm. Output factors
were calculated as the mean response within the central 1×1 cm$^2$ region of each 2D histogram, normalized to the 9×9 cm$^2$ field response. Uncertainties in all output factor calculations are quoted as the standard deviation of the response within the central region.

Dose profiles were first normalized to a central axis response of 100%. 1D relative profiles were then obtained by extracting the response along a slice through the centre of the 2D histograms in the cross-plane direction. Agreement between simulated and measured profiles was evaluated by calculating the percentage of data points with a $\gamma$-index $\leq 1$ based on 3%/3 mm criteria (with dose differences calculated globally relative to the dose at the central-axis and considering only those points above a minimum threshold relative dose of 10%)[10].

3.3. Projection phantom portal dose image
A static 9×9 cm$^2$ beam field size was used to generate an AP projection portal image of an anthropomorphic head phantom using the EPID model.

4. Experimental measurements and model validation
Experimental measurements to validate the MC model were made using the research a-Si EPID described in Section 2.2. An Elekta (Elekta, Crawley, UK) Synergy 6 MV linac with the MLCi multi-leaf collimator was used for all measurements. Images were acquired by averaging 50 frames when delivering a nominal dose rate of 500 MU/min. To minimize backscatter from the treatment couch, the EPID was positioned vertically (i.e. on its side) on the couch and centered on the collimator axis of rotation at a SSD of 160 cm, with the gantry rotated to 90 degrees. Phantoms (as described in Section 2.3) positioned on the couch were centred at the isocentre.

The XIS software package (PerkinElmer, Santa Clara, CA) was interfaced with the research EPID to acquire all images. A gain setting of 4 pF was used with a frame integration time of 499 ms. Images acquired for validation of the transmission factors and field size output factors were both dark-field and flood-field corrected. Flood-field corrections were not applied for validation of EPID relative dose profiles or the anthropomorphic head phantom image as this correction would remove the well-known off-axis detector response[11].

5. Results and Discussion
5.1. Transmission factors
Transmission factors calculated using the MC model and measured using the research EPID are shown in Figure 2. Calculated and measured transmission factors are in excellent agreement, with a maximum percent difference of only 2.0% (occurring for the 40 cm phantom thickness).

5.2. Field size response
Figure 3 shows the calculated and measured variation in EPID response with beam field size when a 20 cm thick solid water phantom is used. The calculated and measured field size responses are in close agreement with the greatest difference of 1.8% occurring for the 3×3 cm$^2$ field size.

5.3. Relative dose profiles
Relative dose profiles calculated using the MC model and measured using the research EPID are presented in Figure 4 for selected beam field sizes between 2×2 and 9×9 cm$^2$ when a 20 cm thick solid water phantom is used. The subplot shows the results of a $\gamma$ comparison between the calculated and measured profiles for each field size using 3%/3 mm criterion. 98% and 99% of profile data points had $\gamma \leq 1$ for the 2×2 and 3×3 cm$^2$ field sizes respectively, whereas 100% of points had $\gamma \leq 1$ for the remaining field sizes. These results demonstrate excellent agreement between the calculated and measured EPID off-axis response.
**Figure 2.** Measured (Exp) and calculated (Sim) EPID transmission factors.

**Figure 3.** Measured (Exp) and calculated (Sim) EPID field size output factors.

**Figure 4.** Calculated relative dose profiles from the standard EPID model using a 20 cm thick phantom of solid water (top panel) and corresponding $\gamma$-values for 3%/3 mm agreement with measured profiles (bottom panel).

5.4. Projection phantom portal dose image

Measured and calculated portal images of an anthropomorphic head phantom are presented in Figure 5. A qualitative comparison of these images demonstrates that the MC model is able to simulate spatial variations in detector response resulting from the use of an inhomogeneous...
phantom representative of human anatomy. The statistical noise present in the calculated image made it difficult to resolve the fine anatomical structures and slight changes in relative density within the phantom. However, macroscopic features such as the orbits and nasal cavity are discernable in the calculated image.

![Image of portal images](image_url)

**Figure 5.** Measured (a) and simulated (b) portal images of an anthropomorphic head phantom.

6. Conclusions

A Monte Carlo model of a standard a-Si EPID that was previously developed for non-transit dosimetry has been extended to transit dosimetry applications. Transmission factors, field size output factors and relative dose profiles were calculated using the model and validated against experimental measurements with excellent agreement. The simulation of an anthropomorphic head phantom portal dose image provides a demonstration for applying this model to predicting EPID images of humanoid anatomy.

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