Development of an independent, Monte Carlo, dose calculation, quality assurance tool for clinical trials

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Introduction

The Imaging and Radiation Oncology Core – Houston (IROC-H) (formerly the Radiological Physics Center) is one of six National Cancer Institute (NCI) funded, quality assurance (QA) offices that provides QA auditing services to institutions participating in NCI funded cooperative clinical trials. IROC-H has developed several programs as a means to efficiently provide dosimetric and QA services to the clinical trial community and to ensure NCI that the institutions participating in clinical trials deliver comparable and consistent radiation doses.

Currently, IROC-H is not able to fully verify the accuracy of IMRT and heterogeneity corrected dose calculations via its own independent calculation. In order to evaluate and judge the accuracy of the TPS predicted dose distributions, a trusted independent dose calculation tool is needed.

For this reason IROC-H began the development of a multiple source model that is executed using the Monte Carlo technique using the Dose Planning Method (DPM) code. While a generic model for Varian 6MV and 10MV beams has been completed, to be a fully functional tool the dose calculation tool must also include models capable of performing dose calculations for Elekta machines and Varian machines operating in flattening filter free (FFF) mode.

Currently, the multiple source model is composed of three analytical components describing the output of a therapeutic megavoltage photon beam. The components correspond to the primary source in the treatment head, an extra-focal scattering source, and a source to model electron contamination in the beam. The analytical model is coupled to the DPM code where simulation of the particle transport occurs resulting in the independent dose calculation tool.

Methods

A three source, Monte Carlo model of Elekta 6MV and 10MV and Varian FFF 6MV and FFF 10MV therapeutic x-ray beams was developed in a two-step process. Energy spectra of each of three sources, a primary source corresponding to photons created in the target, an extra-focal source corresponding to photons originating from scattered events in the linac head, and an electron contamination source, were determined. The two photon sources were determined by an optimization process that fit the relative fluence of 0.25 MeV energy bins to the product of Fatigue-Life and Fermi functions to match calculated percent depth dose (PDD) data with that measured in a water tank for a
10 x 10 cm^2 field.

Off-axis effects were modeled by fitting the off-axis fluence to a piecewise linear function through optimization of relative fluence to match calculated dose profiles with measured dose profiles for a 40 x 40 cm^2 field. Separate 3rd degree polynomials were used to describe the off-axis half-value layer as a function of off-axis angle for the Elekta and Varian FFF models. The model was then commissioned by comparing calculated PDDs and dose profiles for field sizes ranging from 3 x 3 cm^2 to 40 x 40 cm^2 to those obtained from measurements.

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Methods Continued

Benchmarking against clinically realistic cases was performed by using IROC-H anthropomorphic phantoms. Three treatments were delivered for each model a total of three times per treatment plan for a total of 36 deliveries. Plans consisted of an IMRT head and neck plan delivered to the homogenous head and neck phantom as a test of the models ability to calculate dose in small, modulated fields, a 3D conformal plan delivered to a heterogeneous lung phantom as a test of performance in a heterogeneous medium, and an IMRT lung plan delivered to the heterogeneous lung phantom to test the accuracy for modulated fields in a heterogeneous medium.

Patient specific beam modifiers were modeled analytically. First a fluence map with dimensions equal to the jaw settings projected at isocenter and composed of 0.5mm x 0.5mm elements was formed. A transmission of 1% of the fluence along the leaf positions was assigned to the fluence elements blocked by the MLC leaves. Along the final 5mm of leaf tip a linear increase in the leakage was assigned to model the leaf tip. An additional 1% of the fluence was assigned to the fluence elements along the edges of the MLC leaves to model interleaf leakage. A composite fluence map for each beam was formed and segmented into beamlets of similar fluences. Beamlets were then transported using the DPM Monte Carlo code.

Benchmarking agreement was assessed by comparing calculated doses to measured doses from thermoluminescent dosimeters (TLD) and EBT2 radiochromic film. TLD agreement was expressed as a ratio of calculate dose to measured dose and film agreement is reported as a percentage of data passing a ±3%/2mm gamma criterion.

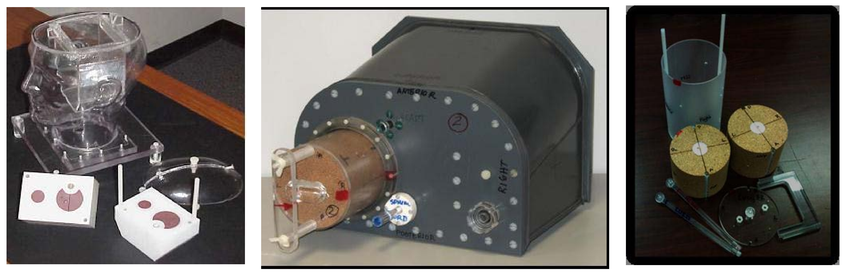

Figure 1: The IROC-H head and neck phantom (left) and lung phantom (center) used in the benchmarking study are shown. The head and neck phantom is shown with the dosimetry insert removed and opened, revealing a transverse view of the mock PTV (crescent shape), secondary PTV (larger of two cylinders) and OAR (small cylinder). The insert to the lung phantom (right) is shown along with removable rods for TLD that are placed at locations consistent with the heart and spine.

Results

Agreement between calculated and measured data was evaluated using ±2%/2mm global gamma criterion for field sizes of 3 x 3, 5 x 5, 10 x 10, 15 x 15, 20 x 20, and 30 x 30 cm^2 for Elekta models and field sizes of 3 x 3, 4 x 4, 6 x 6, 8 x 8, 10 x 10, 20 x 20, 30 x 30, and 40 x 40 cm^2 for Varian FFF models. Along the central axis of the beam 99.6% and 99.7% of all data passed the criterion for Elekta 6MV and 10MV models, respectively. Similarly, average passing percentages for the Varian FFF models were 99.9% and 99.0% for 6MV and 10MV models, respectively. Dose profiles at depths of d_{max}, 5.0, 10.0, 20.0, and 25.0cm agreed with measured data for 99.4% and 99.6% of data tested for Elekta 6MV and 10MV models, respectively. Profiles at depths of d_{max}, 5.0, 10.0, 20.0, and 30.0cm agreed with measured data for 97.8% and 97.9% of data tested for Varian FFF 6MV and FFF 10MV models, respectively.

	PDD Average Agreement	Profile Average Agreement
Elekta 6MV	99.6%	99.4%
Elekta 10MV	99.7%	99.6%
Varian FFF 6MV	99.9%	97.8%
Varian FFF 10MV	99.0%	97.9%

Table 1: Averages of percentage of pixels passing ±2%/2mm gamma analysis for commissioned, Elekta 6MV and 10MV models and Varian FFF 6MV and FFF 10MV models. Averages were taken for field sizes from 3 x 3 cm^2 to 40 x 40 cm^2 for percent depth dose data and does profiles and at depths of d_{max} through 30.0cm for dose profiles.

Elekta benchmarking results in the anthropomorphic phantoms showed average passing rates for the 6MV model using a ±3%/2mm gamma criterion of 87.3%, 87.2%, and 87.9% for IMRT H&N, 3D lung, and IMRT lung deliveries, respectively. Agreement for the 10MV model averaged 90.5%, 89.3%, and 89.9% for the respective plans. Average calculated to measured dose in the PTV TLD for 6MV deliveries was 1.014, 1.030, and 1.004 for the respective plans. Agreement in the 10MV deliveries averaged 1.020, 1.016, and 1.021 for the respective plans.

Varian FFF benchmarking results in the anthropomorphic phantoms showed average passing rates for the FFF 6MV model using a ±3%/2mm gamma criterion of 90.1%, 90.8%, and 91.3% for IMRT H&N, 3D lung, and IMRT lung deliveries, respectively. Agreement for the FFF 10MV model averaged 87.2%, 89.3%, and 93.1% for the respective plans. Average calculated to measured dose in the PTV TLD for FFF 6MV deliveries was 0.984, 1.007, and 1.014 for the respective plans. Agreement in the FFF 10MV deliveries averaged 1.019, 1.003, and 1.020 for the respective plans.

	IMRT H&N	3D Lung	IMRT Lung
Elekta 6MV	87.3%	87.2%	87.9%
Elekta 10MV	90.5%	89.3%	89.9%
Varian FFF 6MV	90.1%	90.8%	91.3%
Varian FFF 10MV	87.2%	89.3%	93.1%

Table 2: Averages of percentage of pixels passing ±3%/2mm gamma analysis for benchmarking studies on anthropomorphic phantoms. Comparisons were performed between calculated and measured dose from radiochromic film in the axial sagittal planes of the head and neck phantom and axial, coronal, and sagittal planes of the lung phantom.

Conclusion

Multiple source models for Elekta 6MV and 10MV and Varian FFF 6MV and FFF 10MV beams were developed based on basic measurement data. The models were validated against open field measurements performed with an ion chamber in a water tank to within ±2% of the maximum dose and ±2mm distance to agreement. The models were then benchmarked against anthropomorphic phantom measurements to within ±3% of the maximum dose and ±2mm distance to agreement. The high degree of accuracy and flexibility of the model make it well suited to be used as a quality assurance tool for clinical trial audits.