Measurement-Based Kilo-Voltage Beam Characterization and Dose Quantification for Radiotherapy Image Guidance

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Abstract–**This study develops a measurement-based approach to characterize the on-board imaging (OBI) system and subsequently perform Monte-Carlo (MC) simulations of imaging dose, independent of manufacturer's specifications. This novel development differentiates the current study from existing MC dosimetry investigations relying on proprietary manufacture's data specifications and rids the difficulty in obtaining and employing such data. The proposed approach consists of an equivalent spectrum module incorporative of intrinsic filtration and an equivalent filter module characterizing the added bowtie filter. Validation studies were performed for a variety of beam energies with both full- and half-bowtie filters. The equivalent spectrum module was validated by evaluating bowtie independence in spectrum estimation. A comparison of quarter value layers (QVLs) derived from full-bowtie spectrum estimations with QVLs determined from half-bowtie measurements and vice versa yielded an estimation-measurement consistency with a discrepancy of less than 2% for all energies evaluated. The end-to-end system was validated by comparing dose distributions from MC simulations based on the measurement-based source/filter model with dose distributions from film measurements for both the full- and half- bowtie scenarios. For all energies evaluated, the average root-mean-square-error (RMSE) is 6.5% for the full-bowtie scenario and 7.05% for the half-bowtie scenario. These results indicate the effectiveness of the proposed method to model the OBI source and filtration components for MC simulations.**

I. INTRODUCTION

Modern radiotherapy utilizes kilovoltage (kV) cone-beam computed tomography (CBCT) intensively for image guidance and monitoring. With the introduction of more comprehensive imaging procedures to the treatment process, there are growing concerns of concomitant imaging dose [1]-[3]. While the dose impact of these imaging procedures has often been regarded as negligible when compared with the intended therapy dose and thus quantified rather loosely, continuous imaging during complex radiation delivery plans and a greater attention to the dose to areas outside of the target volume have yielded the need to investigate and develop a systematic approach to accurately quantify the dose impact of imaging during radiotherapy treatment [4]-[5].

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Monte Carlo (MC) techniques are readily employed to accurately simulate the dose from diagnostic x-ray imaging systems [6]. The accuracy of MC techniques in the area of CT dosimetry is well established [7]-[11]. More recently, MC techniques have been used to simulate the dose from the kV imagers integrated into linear accelerators, such as the Varian on-board imager (OBI) integrated into the Trilogy accelerator [12]-[15]. In order to generate an accurate MC simulation of the OBI dose, detailed information about the x-ray spectrum, internal filtration, added bowtie filtration and beam geometry (i.e. focal spot to isocenter distance, cone angle and collimation) is needed. While much of this information can be referenced from OBI documentation, some of the information, such as energy spectra and bowtie filter descriptions, is proprietary and can only be obtained from the manufacturer with a non-disclosure agreement (NDA). These NDAs are often difficult to obtain, and thus scientific investigators can only perform OBI MC dosimetry research as far as they have obtained the confidential manufacturer data.

While previous attempts to characterize OBI sources have relied heavily upon proprietary manufacturer's data specifications, the purpose of this investigation is to develop an entirely measurement-based approach to characterize the OBI system and subsequently perform MC simulation of the imaging dose. Motivated by a novel measurement-based method developed for conventional CT dose calculation and simulation [16], the aim of this method is to generate an equivalent source model made up of an equivalent spectrum module incorporative of the intrinsic filtration and an equivalent filter module characterizing the added bowtie filter. The goal of the equivalent spectrum module is to generate an x-ray spectrum with a calculated beam behavior that best matches half-value layer (HVL) and quarter-value layer (QVL) values obtained experimentally [17]. The goal of the equivalent filter module is to generate an equivalent full- and half- bowtie filter that attenuates the equivalent spectrum in the same manner that the actual bowtie filter attenuates the actual spectrum by measuring the variation of bowtie filtration across the x-ray beam. With a fully developed equivalent source model, the need for proprietary manufacturer's data specifications for the OBI is eliminated.

In this investigation, we will present the development and calculation of an OBI equivalent source model for a variety of beam energies with both the full- and half-bowtie filter. In order to assess the accuracy of this measurement-based approach, validation studies were performed for an assortment of beam energies with both full- and half-bowtie filters. The equivalent spectrum module was validated by evaluating

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bowtie independence in spectrum estimation. The end-to-end system was validated by comparing dose distributions from MC simulations based on the measurement-based source/filter model with dose distributions from film measurements for both the full- and half- bowtie scenarios.

II. Materials and Methods

A. Measurements

Half value layer (HVL), quarter value layer (QVL) and bowtie filter profile measurements were required to properly develop an equivalent source model for OBI systems. Each measurement was performed for both the full- and half-bowtie filter. Fig. 1 shows the experimental set up for all three measurements. For the HVL and QVL measurements, an initial exposure was made at isocenter, and subsequent exposures were made at isocenter using incremental thickness of aluminum until the resultant exposure was less than one-fourth of the initial exposure. For the bowtie filter profile measurement, an initial exposure was obtained at isocenter (central ray of the bowtie filter). For the full-bowtie filter, the table was moved in small increments in the +z-direction in order to profile the exposure attenuation from the upper half of the bowtie. Because of symmetry about the central ray in the axial plane for the full-bowtie filter, measuring only the upper half of the bowtie is sufficient. For the half-bowtie filter, the table was moved in small increments in the ±z-direction because the lack of symmetry requires both halves of the bowtie to be measured in order to properly characterize the attenuation profile.

B. Equivalent Spectrum Module

The goal of the equivalent spectrum module is to generate an x-ray spectrum with a calculated beam behavior that best matches the HVL and QVL values obtained experimentally. Consistent with (1)-(3) in Fig. 2, the following steps are necessary to execute this module:

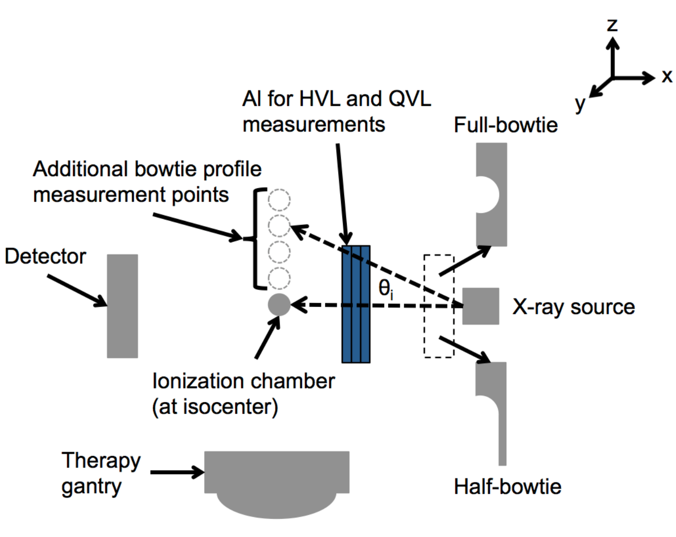

Fig. 1. Diagram of the experimental setup for the HVL, QVL and bowtie profile measurements.

(1) An initial tungsten (W) spectrum is transmitted through a thin, uniform layer of arbitrarily defined intrinsic filtration material. Assuming exponential attenuation, the number of remaining x-rays at each energy is calculated to produce a candidate spectrum.
(2) The candidate spectrum is then transmitted through the central ray thickness of either the full- or half- bowtie filter, and the KERMA in air is calculated.
(3) The spectrum and subsequent KERMA in air resulting from transmitting the candidate spectrum through the central ray of either bowtie plus a thin, uniform thickness of Al is calculated. This step is repeated while incrementally increasing the thickness of Al until the KERMA in air is one-half and one-fourth the initial KERMA in air calculated in step (2). Because KERMA in air is directly proportional to exposure, these thicknesses of Al represent the calculated HVL and QVL of the candidate spectrum.

Steps (1)-(3) are repeated while incrementally increasing the thickness of the intrinsic filtration material until the difference between the measured and calculated HVL and QVL is minimized. The candidate spectrum with the calculated HVL and QVL that best match the measured values is considered the equivalent spectrum.

C. Equivalent Filter Module

The goal of the equivalent filter module is to generate a description of the full- and half- bowtie filter. Consistent with (4)-(6) in Fig. 2, the following steps are necessary to execute this module:

(4) Based on the data acquired from the bowtie filter profile measurement, the ratio of the exposure obtained at each angle, θ_i, to the exposure obtained along the central ray is calculated.
(5) The equivalent spectrum resulting from the equivalent spectrum module is transmitted through a thickness of bowtie filter material deemed to be the center of the equivalent bowtie filter, and the resultant KERMA in air is calculated.
(6) The equivalent spectrum is transmitted through a thickness of Al, and the subsequent KERMA in air is calculated. This step is repeated while incrementally increasing the thickness of Al until the difference between the ratio obtained in step (4) and the ratio of the KERMA in air through the thickness of Al to the KERMA in air from step (5) is minimized. The thickness of Al that minimizes this difference is considered the equivalent path length for θ_i.

Steps (4)-(6) are repeated for each angle measured as part of the bowtie filter profile measurement. Combining the equivalent path length as a function of measured angle produces an equivalent filter description.

D. Validation Experiments

In order to validate the equivalent spectrum module, a comparison of QVLs derived from full-bowtie spectrum estimations with QVLs determined from half-bowtie measurements and vice versa was performed to assess bowtie independence in spectrum estimation.

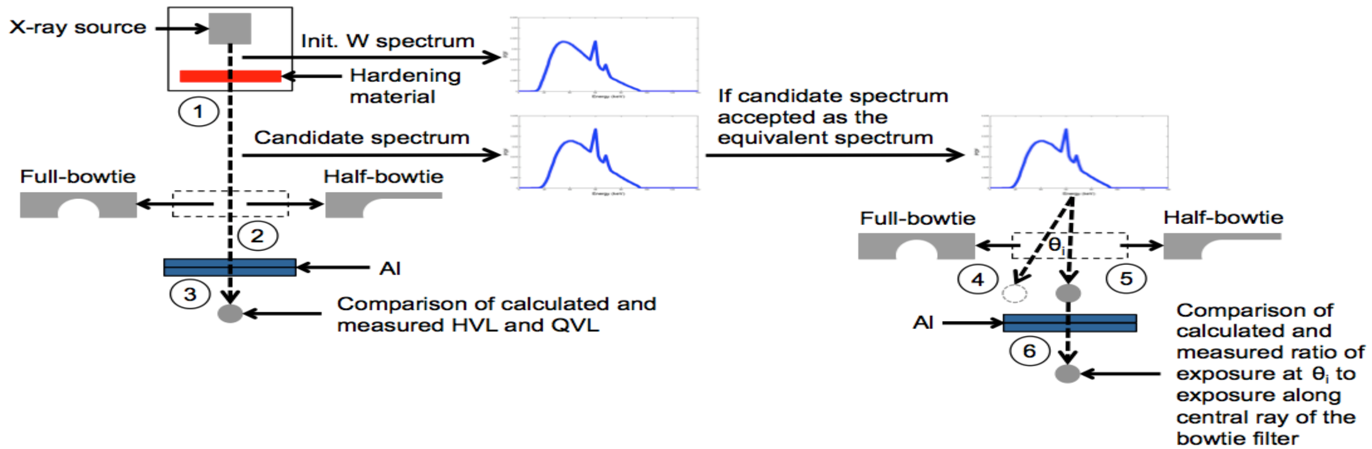

Fig. 2. Diagram of method for generating an equivalent source model using the equivalent spectrum module and the equivalent filter module.

In order to validate the end-to-end system, a comparison of dose distributions from MC simulations with film measurements for both the full- and half-bowtie scenario was performed. Kodak EDR2 10" x 12" film was exposed 6.5 cm deep inside an intensity-modulated radiation therapy (IMRT) phantom at a source-axis distance (SAD) of 100 cm using a beam collimation of 25 cm x 18 cm. MC simulations were performed using MCNPX v2.7.

III. Results

Table 1 shows the difference between the QVLs derived from spectrum estimations and QVLs determined from measurements. E1 is the difference between the QVLs determined from the full-bowtie estimates and the half-bowtie measurements. E2 is the difference between the QVLs determined from the half-bowtie estimates and the full-bowtie measurements. Fig. 3 shows the equivalent spectrums generated using a full- and half-bowtie filter for a 60 kVp and 120 kVp beam (minimum and maximum beam energies used in this study).

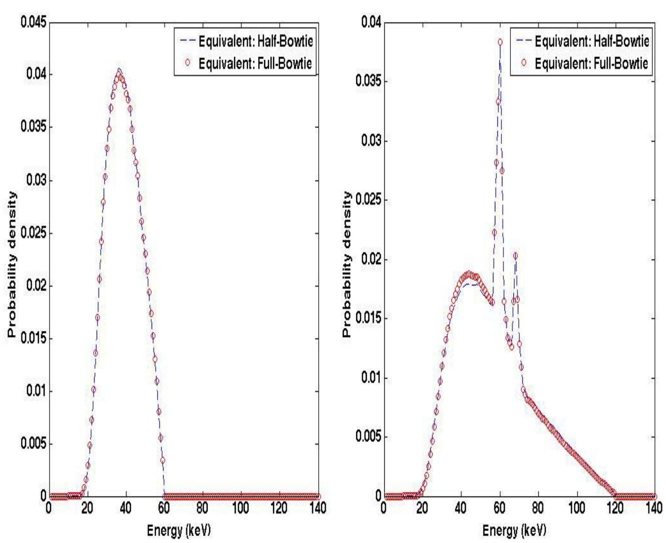

Fig. 3. Full- and half-bowtie equivalent spectrums for a 60 kVp (left) and 120 kVp (right) beam.

TABLE I. QVL COMPARISON

Beam Energy (kVp)	E1 (%)	E2 (%)
60	0.10	0.23
80	1.4	1.4
100	1.1	1.2
120	1.0	1.1

Fig. 4 shows the film measurement and MC simulation relative dose distribution for a 100 kVp beam with a full-bowtie. Table 2 shows the RMSE between relative dose distributions from MC simulations and film measurements for both the full- and half-bowtie scenario. For all energies evaluated, the average RMSE is 6.5% for the full-bowtie scenario and 7.05% for the half-bowtie scenario.

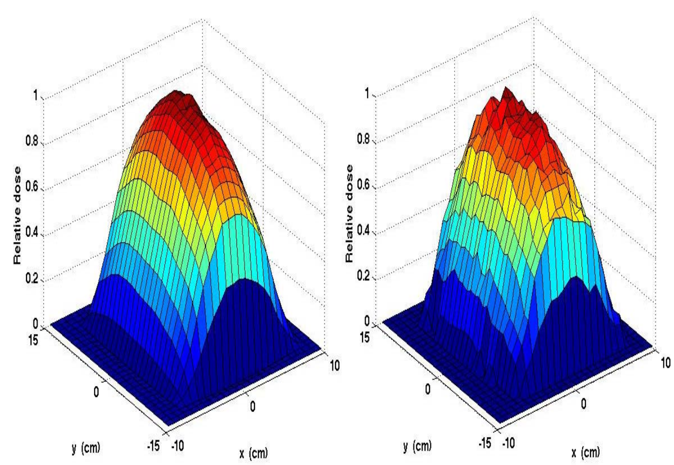

Fig. 4. Film (left) and MC (right) relative dose distribution for a 100 kVp beam with a full-bowtie.

TABLE II. RMSE BETWEEN RELATIVE DOSE DISTRIBUTIONS

Beam Energy (kVp)	Full-Bowtie (%)	Half-Bowtie (%)
60	8.4	9.0
80	6.7	7.3
100	5.7	6.1
120	5.2	5.8

IV. CONCLUSIONS

Table 1 and Fig. 3 both demonstrate the consistency of the spectrum estimations for either full- or half-bowtie measurements. This consistency indirectly validates the consistency and accuracy of the equivalent source approach, as the experimental data are mutually independent, with source and internal filtration being the intrinsic common factor. The agreement observed in Table 2 between the MC and film measurements demonstrates the validity of the end-to-end system.

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