Direct and fast measurement of CT beam filter profiles with simultaneous geometrical calibration

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Purpose: To accurately measure the beam filter profiles from a variety of CT scanner models and to provide reference data for Monte Carlo simulations of CT scanners.

Methods: This study proposed a new method to measure CT beam filter profiles using a linear-array x-ray detector (X-Scan 0.8f3-512; Detection Technology Inc., Espoo, Finland) under gantry rotation mode. A robust geometrical calibration approach was developed to determine key geometrical parameters by considering the x-ray focal spot location relative to the linear-array detector and the gantry's angular increment at each acquisition point. CT beam intensity profiles were synthesized from continuously measured data during a 10° gantry rotation range with calibrated detector response and system geometry information. Relative transmission profiles of nineteen sets of beam filters were then derived for nine different CT scanner models from three different manufacturers. Equivalent aluminum thickness profiles of these beam filters were determined by analytical calculation using the Spektr Matlab software package to match the measured transmission profiles. Three experiments were performed to validate the accuracy of the geometrical calibration, detector response modeling, and the derived equivalent aluminum thickness profiles.

Results: The beam intensity profiles measured from gantry rotation mode showed very good agreement with those measured with gantry stationary mode, with a maximal difference of 3%. The equivalent aluminum thickness determined by this proposed method agreed well with what was measured by an ion chamber, with a mean difference of 0.4%. The determined HVL profiles matched well with data from a previous study (max difference of 4.7%).

Conclusions: An accurate and robust method to directly measure profiles from a broad list of beam filters and CT scanner models was developed, implemented, and validated. Useful reference data was provided for future research on CT system modeling. © 2016 American Association of Physicists in Medicine [https://doi.org/10.1002/mp.12024]

Key words: beam filtration, bowtie, computed tomography, geometrical calibration, transmission

1. INTRODUCTION

In order to accurately describe and model the system output of a modern diagnostic CT scanner and to estimate radiation dose to a patient, it is necessary to obtain information about the x-ray fluence distribution in space,^{1–7} $\Phi(kV, E, \theta)$, which is determined by the unfiltered raw spectrum $\Phi_0(kV, E)$ and the added x-ray beam filtration thickness $x(i, \theta)$, where i is the index for different filter component, and θ is the angle from the central ray of the beam, which is typically constrained within the fan beam plane. While the unfiltered raw x-ray spectra had been well modeled, the mere measurement of the traditional half-value-layer (HVL) at the center of the beam is not sufficient due to the width of CT fan-beam and, more importantly, the existence of beam shaping filters

typically referred to as bowtie filters⁸. Detailed information of a specific bowtie filter, including the thickness and material distribution along the fan angle, is proprietary. Only limited data may become available even under non-disclosure-agreements (NDA). Clearly, non-invasive methods through physical measurements are attractive to medical physics researchers. Three different types of measurements have been explored to provide information related to the spatial distribution of the x-ray fluence from CT systems:

- Directly measured beam intensity profiles:

$$I(kV, \theta) = \int_0^{kV} \Phi_0(kV, E, \theta) e^{-\sum_i x(i, \theta) \mu(i, E)} D(E) dE \quad (1)$$

Where $\mu(i, E)$ is the linear attenuation coefficient of the filter component, i , and $D(E)$ is the response of a certain detector and will be covered in more detail later. Due to the existence of the bowtie filter, this profile (as a function of kV, mAs, and distance to the focal spot) has its maximum value at $\theta = 0$.

- HVL profiles: $HVL(kV, \theta)$.

This method provides more overall information in terms of “beam quality profile” as compared to the first method. However, it requires tremendous effort to perform and typically provides limited angular sampling along the fan beam plane. Poirier et al. performed HVL measurements along the transverse axis (across scan FOV) of a cone-beam CT system.⁹ Sommerville et al. measured the HVL at multiple locations across the CT fan-beam with the CT gantry kept stationary and demonstrated improved accuracy of dose estimation given this additional HVL information.¹⁰ Randazzo and Tambasco also proposed an improved approach to measure off-center HVL with a rotational CT gantry, utilizing the concept of “COBRA” (introduced below).¹¹ This type of profile has its minimum value at $\theta = 0$ given the increasing thickness of the bowtie toward the edges of the fan beam.

- Relative transmission profiles through a certain filter:

$$\Gamma(kV, \theta) = \frac{I(kV, \theta)}{I(kV, 0)} \quad (2)$$

where $I(kV, \theta)$ can be determined by Eq. (1). As shown by many previously published works (discussed below), this method can yield very consistent results given the normalization step by the intensity measured at the bowtie center, i.e., $I(kV, 0)$. Thus the factors including the measuring distance and tube mAs can be cancelled out for different experiment setup. Advanced measurement approaches had also been presented for a rotating CT gantry. However, by definition, $\Gamma(kV, 0)$ is always equal to 1. Thus, this type of transmission profiles does not have information related to the center of the bowtie filter and can only provide “relative” transmission to the bowtie center.

If the ultimate goal is to decipher the beam filter components and their angular distribution, all three methods above are indirect approaches, given the integration nature related to measurement of poly-energetic x-ray photons [Eq. (1)]. Turner et al. proposed a practical two-step approach to generate equivalent energy spectra and filtration models based on physical measurements¹². The first step was to measure the central beam HVL, which was followed by the second step to measure the relative filter profile (again including the bowtie filter and the flat filter) of the actual spectrum across the fan beam. The measured results from these two steps were combined by assuming an arbitrary thickness/material at the center of the beam filter. With this generalizable model, it is sufficient to

measure the beam filtration profiles of the x-ray beam filters from a specific scanner while avoiding the challenge to determine their exact composition/shape.

Despite these previous efforts, however, it is still a non-trivial task to accurately measure the beam filtration profile, using different radiation detectors including ion chambers,^{12,13} radiochromic films,¹⁴ and solid state detectors.^{3,15,16} The major challenges include the high-speed rotation of the CT gantry, the large variations in the beam quality from the center to the edge of the beam filter, limited choices of radiation detectors for this specific purpose, and the limitation from available scan protocols. Boone initially proposed the “COBRA” method to use a high-speed/real-time detector to continuously sample the air kerma when it is placed at the edge of the gantry.¹⁷ The transmission profile can be analytically determined from the measured signal train while the x-ray source-to-isocenter distance and chamber-to-isocenter distance are known. The theoretical model has been validated by McKenney et al.¹⁵ and later further improved by Whiting et al.¹³ when considering the relative size of the detector as compared to beam collimation width. Due to the limitation from a single point measurement, multiple gantry rotations were necessary to achieve desired data sampling. Whiting et al. also proposed a low-cost alternative to measure transmission profiles using radiochromic films under gantry rotation mode while sufficient “collimation” for discrete spots on the film can be achieved by steel bars to block radiation signal from oblique angles.¹⁴ The sampling accuracy was limited by the available opening locations from the pre-fabricated metal bars. The same task became relative easier when the CT gantry can be parked at a fixed location under service mode. Turner et al. measured filter transmission profiles with a stationary gantry while translating an ion chamber linearly across the fan beam.¹² Sommerville et al.¹⁰ and Randazzo and Tambasco¹¹ measured HVL profiles utilizing a stationary gantry. Li et al. proposed a new method to use a solid state linear-array detector to directly measure the x-ray beam profile along the fan angle with a stationary gantry, with and without a bowtie filter.³ Thus, a slightly different profile of a specific bowtie filter could be determined by:

$$\Gamma_{\text{bowtie}}(kV, \theta) = \frac{\int_0^{kV} \Phi_0(kV, E, \theta) e^{-\sum_i x(i, \theta) \mu(i, E)} D(E) dE}{\int_0^{kV} \Phi_0(kV, E, \theta) e^{-\sum_{i \in \text{flat filter}} x(i, \theta) \mu(i, E)} D(E) dE} \quad (3)$$

Compared to Eq. (2), $\Gamma_{\text{bowtie}}(kV, 0)$ from Eq. (3) normally does not equal to 1 and provides more complete transmission information of the bowtie filter, including the bowtie center.

For all the above mentioned approaches, one key common challenge remain unsolved is the system geometrical calibration. The accuracy of the measured beam filter profiles depends on the related geometrical parameters, including the focal spot to detector distance, focal spot to

isocenter distance, and the angular location of the focal spot if it was under the gantry rotation mode. In this study, we developed a method of using a high-speed, high-resolution, linear detector (very similar to the one used by Li et al.,³ but a different model) to measure CT filter profiles (both intensity and transmission profiles) under the gantry rotation mode, simultaneously utilizing the information from two fiducial markers to determine related geometrical parameters. Combining these measured results with theoretical modeling, equivalent aluminum thickness profiles were determined as the end results. To the best of our knowledge, this is the first study to incorporate an accurate geometrical calibration and to achieve the 0.1° angular resolution of CT beam filter profiles for a large list of scanner models (nine scanners and nineteen sets of filters).

2. METHODS AND MATERIALS

2.A. Linear detector calibration

This study used a GOS scintillator based indirect detector (X-Scan 0.8f3-512, Detection Technology Inc, Espoo, Finland). This linear detector (referred to as “DT detector” below) is composed of an array of 1×640 pixels with pixel dimension of $0.8 \text{ mm} \times 0.7 \text{ mm}$, which provides a linear coverage range of 512 mm ($0.8 \text{ mm/pixel} \times 640 \text{ pixels}$) and that is sufficiently wide to capture the entire CT filter profile from a single acquisition. The linearity of the detector’s response in regard to the signal gain and integration time was previously verified by our group.¹⁸ Due to the strong primary x-ray beam intensity from CT scanners, we chose the lowest gain combination and shortest integration time (0.24 ms) for this study.

It is well known that the measured signal from solid state detectors typically has a strong dependence on the incident angle of x-ray beam and the related gain parameter of each individual pixel. Therefore, we had to characterize the angular response of the DT detector and then the gain variation among each pixel. Both calibrations were performed from a GE LightSpeed Xtra scanner, while the DT detector was placed at isocenter and with the sensitive strip aligned to the fan beam, laterally centered within the gantry. The angular response was calibrated with gantry rotation mode and the gain variation was calibrated with gantry stationary mode, respectively. The gain calibration was performed without any bowtie filters in the primary beam. A beam collimation of 5 mm ($4 \times 1.25 \text{ mm}$) was selected to sufficiently cover the DT detector pixels in the longitudinal direction.

For the angular response calibration with gantry rotation mode, the continuous signal train from a single pixel was recorded with the time intervals of 0.24 ms through a complete CT scan of 2 s. Through the geometrical calibration (to be introduced later), the x-ray focal spot’s angular location at each time point was determined. For the DT detector pixel that was located at the isocenter, its response was associated to the x-ray source’s angular location, thus the x-ray incident angle, and not affected by the beam filter profile. This

characterization was repeated for all four tube voltages (80, 100, 120, and 140 kV) and the angular response of the DT detector, $f(\beta)$, was determined as a function of x-ray incident angle, β , and for each kV. Smooth analytical functions fitted to the measured data were produced for easy implementation of the angular response correction.

For the gain variation calibration, under the same setup, continuous acquisitions of 2 s long stationary exposures on the DT detector were averaged for each kV. After correcting for the detector signal offset, inverse-square law, and the angular response, each individual pixel gain was normalized to the one with the highest Analog-to-Digital Unit (ADU). The resulting gain function was used to correct for all the profile data acquired from the DT detector in this study.

2.B. Geometrical calibration and beam intensity profile synthesis

As shown in Fig. 1, four key parameters related to CT beam profile measurement were to be determined under gantry rotation mode:

- The x-ray source to the isocenter distance (SID , mm);
- The DT detector location in y direction (d_{DT} , mm);
- The central ray location on DT when the x-ray tube is at 12 o’clock position (u_0 , pixel);
- The angular increment of the focal spot within each data acquisition interval ($d\theta$, degree).

With the introduction of two small fiducial markers (BB1 and BB2), accurate geometrical reference information can be provided without interfering with the eventually measured beam intensity profile. From a full rotation of CT scan, the physical locations of the two BBs (x_1, x_2, y_1, y_2) can be determined from the reconstructed CT image. At a certain time point, t , the projection locations of each BB on the DT detector will be $u_{BB1}(t)$, $u_{BB2}(t)$, and the distance between the two locations is $L_{BB}(t) = u_{BB2}(t) - u_{BB1}(t)$. A simple relationship can be set up as:

$$\frac{L_{BB}(t)}{L_0} = \frac{SID \cos(\theta_0 + t \cdot d\theta) - d_{DT}}{SID \cos(\theta_0 + t \cdot d\theta) - d_{BB}} \quad (4)$$

Where $L_0 = |x_2 - x_1|$, $d_{BB} = (y_1 + y_2)/2$, and θ_0 is the hypothetical initial tube location when both markers start appearing in the DT detector signal profile.

If we introduce a single function $X(t)$, which is a magnification factor for the distance between the BB’s being projected onto the linear detector:

$$X(t) = \frac{L_{BB}(t)}{L_0} = 1 + \frac{-d_{DT} + d_{BB}}{SID \cos(\theta_0 + t \cdot d\theta) - d_{BB}} \quad (5)$$

With a regression model between $X(t)$ and t , using a curve fitting toolbox (cftool; MATLAB, Natick, MA, USA), three key parameters, SID , d_{DT} , $d\theta$, together with θ_0 , can be directly determined by the fitting coefficients. The last parameter, u_0 ,

FIG. 1. Geometrical calibration model. The CT system isocenter is at $x = 0$, $y = 0$. The DT detector has a one-dimension axis of u , which is parallel to the x -axis and located at $y = d_{DT}$. [Color figure can be viewed at [wileyonlinelibrary.com](#)]

can be determined by first locating the time point when the x -ray source is closest to $x = 0$, so

$$t_0 = -\frac{\theta_0}{d\theta} \quad (6)$$

Then,

$$u_0 = \frac{L_{BB}(t_0)}{L_0} |x_1| + u_{BB1}(t_0) \quad (7)$$

With all four geometrical parameters determined, the CT beam intensity profile can be synthesized from the same data set. As shown in Fig. 2, for a specific DT detector acquisition at time point t , the gantry angle will be at $\theta(t) = \theta_0 + t \cdot d\theta$ and the x -ray source will be at:

$$xs(t) = SID \cdot \cos(\theta), ys(t) = SID \cdot \sin(\theta). \quad (8)$$

For a specific DT pixel indexed at i , its location is fixed at:

$$x(i) = (i - u_0) \times 0.8, y(i) = d_{DT} \quad i = 1 : 640 \quad (9)$$

so is its distance to the isocenter: $b(i) = \sqrt{x(i)^2 + y(i)^2}$. The x -ray incident angle to this pixel is:

$$\beta(t, i) = 90^\circ + \tan^{-1} \left[\frac{xs(t) - x(i)}{ys(t) - y(i)} \right] \quad (10)$$

The distance between the focal spot and the i th pixel is:

$$ds(t, i) = \sqrt{[x(i) - xs(t)]^2 + [y(i) - ys(t)]^2} \quad (11)$$

The fan angle can therefore be determined by:

$$\alpha(t, i) = \cos^{-1} \left[\frac{ds(t, i)^2 + SID^2 - b(i)^2}{2 \cdot SID \cdot ds(t, i)} \right] \quad (12)$$

FIG. 2. Beam intensity profile synthesis model. A single measurement, $DT(t, i)$, which was recorded at time point, t , by the detector pixel, i , was attributed back to the filter profile at fan angle $\alpha(t, i)$, using the parameters determined from the geometrical calibration. [Color figure can be viewed at [wileyonlinelibrary.com](#)]

At the end, the DT detector signal (after the detector offset and gain correction) measured at pixel i can be correctly put back to the beam intensity profile at the corresponding fan angle, $\alpha(t, i)$,

$$I(\alpha(t, i)) = \frac{DT(t, i)}{ds(t, i)^2 f(\beta(t, i))} \quad (13)$$

Here the beam intensity profile will be a function of fan angle with iso-distance to the x -ray source. The above approach will generate an oversampled profile at very fine angular sampling. In this study, the DT detector data acquired from a small gantry angle range of $\pm 5^\circ$ was used to synthesize the profile. For a 1 s rotation, a beam intensity profile will be synthesized from $640 \times (10/360) \times (1000/0.24) \approx 7.4 \times 10^5$ data points. The final profiles reported below were re-binned to an angular resolution of 0.1° .

Using Eq. (3), the relative transmission profiles $\Gamma(kV, \theta)$ can be also determined with the same angular resolution.

2.C. Implementation and data acquisition

As an example, Fig. 3 shows how the DT detector was placed along the fan-beam direction within the CT scanner gantry. For certain scanner models, the DT detector was placed further away from the isocenter to avoid saturation and then shifted laterally to maintain fan beam coverage (as indicated by d_{DT} and u_0 in Table I). A wire phantom with two metal wires taped on a foam base was placed above the DT detector. Cautions were taken to ensure that only the wires were intercepting the x -ray beam (thus no attenuation from the foam). The beam

FIG. 3. Setup for beam intensity profile measurement and geometrical calibration. The lower picture is showing the relative locations of the wire markers in regard to the x-ray beam (indicated by laser). [Color figure can be viewed at wileyonlinelibrary.com]

intensity profile measurements were performed with gantry rotation mode, simultaneously including the geometrical calibration. The measured data sets were first corrected for detector offset and gain variation. As shown in Fig. 4, the location of each marker can be automatically tracked through the rotational acquisition by calculating the local center of mass within a 10-pixel window. For that calculation, a linear de-trending was applied to remove the impact from the beam filter profile. The extracted marker coordinates were fit into the model described by Eq. (5). An example is shown in Fig. 4(c).

Following the geometrical calibration, the data were processed using Eq. (6–13) and the small regions affected by the markers were excluded from the final profile synthesis. An example set of measurements is shown in Fig. 5.

The abovementioned approach was implemented on nine representative CT scanners from our hospital (Table I). A total of 19 sets of beam filter profiles were measured. All the measurements were performed with axial scan mode while the table kept stationary. Following the public available user manuals, different beam filters (identified by the name of the corresponding bowtie filter) were inserted under various protocols available on the scanner. The majority (except for one) of the beam filters were measured with four different kVs (80, 100, 120, 140). The nominal SID information available from the CT DICOM header was also used to validate the geometrical calibration method.

2.D. Equivalent aluminum thickness profiles

For the practical purpose of modeling a specific bowtie filter in Monte Carlo simulation of CT acquisitions, it is more useful to derive a single material bowtie (typically aluminum) and provide the equivalent aluminum thickness profiles for each individual kV/bowtie combination. Here we adopted the equivalent spectrum approach by Turner *et al.*,¹² together with theoretical x-ray spectrum modeling. The first step is to determine the equivalent aluminum thickness at the bowtie center by matching the HVL values provided by manufacturer's technical reference manuals. An analytical calculation platform was setup

TABLE I. CT scanner information and geometrical calibration results.

Scanner model	Nominal SID (mm)	Time per rotation (s)	Beam filter	SID (mm)	Measured parameters		
					u_0 (pixel)	d_{DT} (mm)	$d\theta$ (°)
GE discovery CT750 HD	538.52	2	Large	538.24	321.94	−3.66	0.0429
			Medium	538.30	321.95	−3.67	0.0429
			Small	538.14	321.99	−3.57	0.0429
GE light speed xtra	606	2	Large	606.74	318.82	1.72	0.0431
			Small	606.74	319.53	1.76	0.0430
GE light speed VCT	541	2	Large	541.48	319.35	−6.41	0.0429
			Medium	541.48	318.73	−6.45	0.0429
			Small	541.47	319.00	−6.43	0.0429
GE discovery CT590 RT	606	2	Large	606.42	321.44	2.46	0.0429
			Small	606.43	321.93	2.48	0.0429
Siemens sensation cardiac 64	570	1	Standard	570.13	299.12	−149.51	0.0861
Siemens SOMATOM Definition flash	595	1	Standard	595.48	259.11	−107.81	0.0854
		1	Wide	595.46	259.14	−107.78	0.0856
		0.33	Narrow	595.19	258.00	−109.26	0.2562
Siemens SOMATOM Definition edge	595	1	Standard	595.44	264.21	−111.26	0.0844
		0.33	Narrow	594.99	262.91	−112.38	0.2555
Siemens SOMATOM force	595	1	Standard	595.27	261.65	−101.52	0.0855
Philips brilliance iCT 256	570	0.75	Large	570.40	333.26	−1.88	0.1150
		1	Medium	570.25	333.97	0.82	0.0862

FIG. 4. Marker tracking and data fitting for geometrical calibration. (a) DT data shown as a 2D image, after correction of signal offset and gain variation. Note the beam intensity profile was recorded at more than 1600 time points on DT for a single 2 s rotation within a gantry angular range of 68.8°. (b) Auto-tracking of the marker locations, overlaid on the image. (c) Data fitting between $X(t)$ and t . There is a unique $X(t)$ value for each specific time point t . The appeared overlapping of data points is due to the fine sampling in the time domain. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 5. CT beam intensity profile examples and data binning. The binned data were re-binned/averaged from the raw data to 0.1° accuracy. [Color figure can be viewed at wileyonlinelibrary.com]

using the Spektr software package.¹⁹ In Spektr, we started with an “unfiltered” tungsten anode x-ray spectrum from TASMIP²⁰ with no inherent filtration and 0% ripple, $\Phi_0(\text{kV})$. Following

the process shown in Fig. 6, we could match the bowtie center’s HVL values (to an accuracy of 0.01 mm) by iteratively adding aluminum filters, with a step of 0.01 mm.

Once the equivalent aluminum thickness at the bowtie center, $Alx(kV,0)$, was determined for each kV and bowtie combination, it was used as the anchor point in the Spektr platform to match the measured transmission profiles from DT. The diagram of this process is shown in Fig. 7. The key of this step is the modeling of the response of the DT detector, $D(E)$, as shown in Eq. (1). With the information from the detector manufacturer, we used a 0.8 mm thick GOS block plus a 0.1 mm Al window as:

$$D(E) = k_{GOS} e^{-\mu_{Al}(E) \cdot 0.01} E (1 - e^{-\mu_{GOS}(E) \cdot 0.08}) \quad (14)$$

The constant k_{GOS} is related to the conversion efficiency of the electronic component of the detector and was set as 1 for convenience, since it will be cancelled out in the calculation of relative transmission [Eq. (2)]. The model of the DT detector was validated through a separate experiment (details in Section 2.E.2). The equivalent aluminum thickness at a specific fan angle was determined by finding the proper aluminum thickness (with an accuracy of 0.01 mm) that minimizes the differences between the calculated and measured transmission values.

FIG. 6. Process to determine the bowtie center filtration. This process was carried out for each kV/bowtie combination. [Color figure can be viewed at wileyonlinelibrary.com]

2.E. Validations

Three separate validations were performed to confirm the accuracy of the proposed method.

2.E.1. Geometrical calibration

In order to validate the geometrical calibration method and the beam intensity profiles measured with gantry rotation mode, additional gantry stationary acquisitions of beam intensity profiles were performed under service mode for the GE LightSpeed Xtra scanner using the DT detector. With all the acquisition technique set up similarly to the gantry rotation mode, the acquired profiles of two different bowtie filters with four different kVs were acquired under gantry stationary mode. The comparison between the rotation and stationary mode provided a validation of the proposed geometrical calibration method.

2.E.2. Detector response of DT and the determined aluminum thickness

To validate the proposed DT detection model [Eq. (14)] and the accuracy of the determined equivalent aluminum thickness, we performed a “virtual bowtie” experiment using both the DT detector and a 0.6 cc thimble ionization chamber ($10 \times 6 - 0.6$ CT, RadCal, Moravia, CA, USA). With an effective length of 19.7 mm, the ion chamber was calibrated by the manufacturer with equipment traceable to NIST standard. We considered this experiment to be a “virtual bowtie” test, because in this test, the “profile” of the “virtual bowtie” was constructed solely by changing the thickness of 1100 aluminum foils within the x-ray central beam. This setup gave us a “bowtie” profile with exactly known material and thickness. This validation was performed on the GE LightSpeed Xtra scanner

FIG. 7. Process to determine the equivalent aluminum thickness at fan angle, θ . All the parameters involved here were analytically calculated in Spektr, except for the measured transmission, $\Gamma_m(kV, \theta)$. [Color figure can be viewed at wileyonlinelibrary.com]

with gantry stationary under the service mode, without any actual bowtie filters in the primary beam. As shown in Fig. 8(a), the DT detector was placed perpendicularly to the fan-beam direction and at 120 mm below the isocenter within the CT gantry. This relative long distance from the x-ray source, a very narrow beam collimation ($4 \times 0.625 = 2.5$ mm), and the small DT pixel size allowed us to create a close-to-ideal narrow beam condition for measurement. With the x-ray tube kept stationary at the top of the gantry, the sensitive strip of the DT detector was aligned laterally with x-ray beam center using the scanner's positioning laser. The radiation intensity was measured by a single pixel from the DT detector at different kVs (80, 100, 120, 140) with the increasing thickness of 1100 aluminum foils (ranging from 0 to 31.5 mm, with combinations of 0.5, 1, and 2 mm layers) added between the source and detector. As shown in Fig. 8(a), the bottom of the foil support is

FIG. 8. Experiment setup of the validation between (a) the DT detector and (b) a 0.6 cc ion chamber. Dashed lines indicate the center of x-ray beam. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 9. Angular response and gain variation of the DT detector. (a) Angular response data, $f(\beta)$. The smooth fitting was a summation of two sine functions. (b) Zoom in plot for the range between 60° to 120° . (c) The gain variation function of the DT detector. [Color figure can be viewed at wileyonlinelibrary.com]

~42 cm from the detector to minimize scatter. For the ion chamber experiment, the setup is very similar [Fig. 8(b)]. Two sets of lead collimators were added below the aluminum support (lead plates) and above the ion chamber (soft lead shields) to minimize the impact of scatter on the measured signal.

For both detectors, the measured signals were then normalized by the signal with 0 mm aluminum added to achieve the measured “transmission profile”. Following the same process in Section 2.D, the equivalent aluminum thickness was determined through the comparison between measured transmission profiles to theoretically calculated profiles using Spektr. Since the single material in this test was known as aluminum, the minimization condition in Fig. 7 was set to be the least square summation of the differences in transmission for all four kVs. The DT detector response was modeled as Eq. (14) and the ion chamber response was modeled as air kerma from an ideally calibrated chamber:

$$D(E) = k_{air} E \left(\frac{\mu_{en-air}(E)}{\rho} \right) \quad (15)$$

The constant, $k_{air} = \frac{8.76 \times 10^{-3}}{5.43 \times 10^5}$, gives the unit of mGy for the final integrated signal. This factor was also cancelled out through transmission calculation.

The equivalent aluminum thickness “profiles” determined by DT and ion chamber were compared to the nominal aluminum thickness and the percentage difference was also calculated.

2.E.3. Bowtie profile validation

For the purpose of independent validation of the measured bowtie profiles, HVL profiles data from a GE Optima CT580

FIG. 10. Transmission profile results from GE scanners, as identified by the names of corresponding bowtie filters. (a) Discovery CT750 HD. (b) LightSpeed Xtra. (c) LightSpeed VCT. (d) Discovery CT590 RT. [Color figure can be viewed at wileyonlinelibrary.com]

scanner (from the study by Randazzo and Tambasco¹¹) were generously provided by the authors. As from GE's technical reference manual, the Optima CT580 share the same x-ray tube and bowtie profiles with the Discovery CT590 RT scanner therefore those data can be compared with the results calculated from this study from a CT590 RT scanner. The HVL profiles were calculated using the Spektr function "SpektrHVLn", with only a small modification of the HVL accuracy, from 0.001 mm to 0.0001 mm.

3. RESULTS

3.A. Angular response and gain variation of the DT detector

The angular response of the DT detector, $f(\beta)$, is shown in Figs. 9(a) and 9(b). There is only weak dependence of this distribution on the kV. Nevertheless, in this study, four different $f(\beta)$ functions (fitted to the summation of two sine functions) were used to take this subtle dependence of kV into

account. As shown in Fig. 9(b), for incident angles between 60° to 120° , which is the pertinent angular range for this study, the detector response changed less than 10%.

The DT detector gain variation results are shown in Fig. 9(c). It is worth noting that these data were corrected for the angular response, $f(\beta)$. Due to the very subtle dependence on the kV, an averaged gain variation function (solid line) was used to correct for all the acquired DT data. It is noticeable that there were pixels with very low gains (pointed by the arrows, typically only one or two pixels) due to the boundaries between two adjacent detector modules. These pixels were treated as dead pixels and the interpolated values from neighboring pixels were used to replace them.

3.B. Beam filter transmission profiles

The transmission profiles measured from nine representative CT scanners listed in Table I are further compared and analyzed in (Figs. 10–12). The beam filter

FIG. 11. Transmission profile results from Siemens scanners, as identified by the names of corresponding bowtie filters. (a) Sensation Cardiac 64. (b) SOMATOM Definition Flash. (c) SOMATOM Definition Edge. (d) SOMATOM Force. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 12. Transmission profile results from a Philips Brilliance iCT 256 scanner, as identified by the names of corresponding bowtie filters. Only three kV choices are available for the medium filter. [Color figure can be viewed at wileyonlinelibrary.com]

transmission profiles were identified by the corresponding bowtie filter names from the manufacturer's public manual information.

3.C. Equivalent aluminum thickness profiles

Figures 13–15 show the data of equivalent aluminum thickness profiles determined for the nine scanners. For clearer data presentation, these profiles are shown as relative thickness by subtracting the central aluminum thickness, $Al_n(kV, 0)$. The detailed data of the bowtie center aluminum thickness were attached in the supplemental material of this manuscript.²⁰

3.D. Validation results

Figure 16 compares beam intensity profiles measured with two different gantry modes, rotational (solid lines) and stationary (astericks). With the maximum difference of 3%,

FIG. 13. Aluminum thickness profiles from GE scanners, as identified by the names of corresponding bowtie filters. All the curves in each group are shown with 140 kV on top and 80 kV at the bottom [example shown in (b)]. (a) Discovery CT750 HD. (b) LightSpeed Xtra. (c) LightSpeed VCT. (d) Discovery CT590 RT. [Color figure can be viewed at wileyonlinelibrary.com]

good agreement can be observed for both filters, providing a solid validation for the geometrical calibration method. It is worth noting that these profiles are shown as the directly measured intensity profiles [Eq. (1)] and thus depend on the tube mAs.

Figure 17 compares the aluminum thickness profiles estimated by DT and ion chamber, as functions of the nominal aluminum thickness. Both detectors provided relatively accurate estimates. For the aluminum thickness ranging from 0 to 31.5 mm, the mean percentage difference to the nominal thickness is 1.38% for DT and 1.83% for ion chamber, respectively. The mean percentage difference between DT and ion chamber is 0.4%. This result validated the accuracy of the detection model [Eq. (14)] of DT and the calculation approach of the equivalent aluminum thickness profiles.

Figure 18 compares the estimated HVL profiles from the GE CT590 RT scanner to the data measured from a previous study by Randazzo and Tambasco,¹¹ with a maximal percentage difference of 4.7%.

4. DISCUSSION

As shown in Fig. 17, with an accurate modeling of the detector response, both the DT detector and the ion chamber can accurately determine the equivalent aluminum thickness (with an average error < 2%) by matching the measured transmission data. The advantages of using DT include the high absorption efficiency of the solid state scintillator, fast read-out time, high spatial resolution, and large fan-angle coverage. With the simultaneous geometrical calibration, Simultaneous geometrical calibration enabled the utilization of sub-mm resolution data under gantry rotation mode. Therefore, with a single gantry rotation, the full profile of one beam filter could be measured with relative high angular accuracy (0.1° in this study).

One limitation of this study was that the HVL values at the bowtie center were not directly measured. By using the HVL values provided by the manufacturers, the bowtie center filtration was first determined and then used as the anchor point to determine the entire equivalent aluminum thickness

FIG. 14. Aluminum thickness profiles from Siemens scanners, as identified by the names of corresponding bowtie filters. All the curves in each group are shown with 140 kV on top and 80 kV at the bottom [example shown in (a)]. (a) Sensation Cardiac 64. (b) SOMATOM Definition Flash. (c) SOMATOM Definition Edge. (d) SOMATOM Force. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 15. Aluminum thickness profiles from a Philips Brilliance iCT 256 scanner, as identified by the names of corresponding bowtie filters. Only three kV choices are available for the medium filter. [Color figure can be viewed at wileyonlinelibrary.com]

profile. Further work on this topic should include an accurate and fast approach to measure the bowtie center HVL for each bowtie/scanner combination, as previously proposed by McKenney *et al.*²¹ Independent to the HVL values at the bowtie center, the transmission profiles provided in this study can still be utilized to achieve more accurate aluminum thickness profiles.

According to manufacturers' user manuals, the use of a specific bowtie filter is normally associated with a set of specific clinical protocols. One of the main challenges for this study was to enable a proper protocol while maintaining the table stationary for axial scan. For example, the Narrow bowtie for Siemens scanners and the Medium bowtie for Philips scanners are only used for cardiac applications and, for this case, simulated EKG signals had to be used to finish a cardiac scan. Under certain circumstances, however, a proper protocol may not be available to trigger a bowtie filter under axial scan mode. The method proposed in this study can be alternatively performed with helical scan protocols if the

FIG. 16. Validation between rotational and stationary mode. Beam intensity profiles for (a) the large bowtie and (b) the small bowtie. Relative differences between the stationary and rotational measurements, for (c) the large bowtie and (d) the small bowtie. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 17. Validation of estimated aluminum thickness profiles between DT and ion chamber. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 18. Comparison with a previous study. HVL profiles compared with data from Randazzo and Tambasco (Ref. 11) for three different kVs. Data courtesy: Dr. Mauro Tambasco. [Color figure can be viewed at wileyonlinelibrary.com]

DT detector is supported by an independent stand which is not attached to the scanner table.

5. CONCLUSIONS

In this work, we developed a new method to measure CT filter profiles, using a linear-array solid state detector. With the highly accurate geometrical calibration, CT beam intensity profiles were synthesized from data acquired under the gantry rotation mode. Relative transmission profiles and equivalent aluminum thickness profiles were further determined and validated. High quality filter profiles were reported for a large list of CT scanner models and such data are expected to be useful in CT performance studies, especially involving radiation dose simulations.

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CONFLICTS OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S1: Bowties center filtration.