Skin dose mapping for non-uniform x-ray fields using a backscatter point spread function

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Abstract

Beam shaping devices like ROI attenuators and compensation filters modulate the intensity distribution of the x-ray beam incident on the patient. This results in a spatial variation of skin dose due to the variation of primary radiation and also a variation in backscattered radiation from the patient. To determine the backscatter component, backscatter point spread functions (PSF) are generated using EGS Monte-Carlo software. For this study, PSF's were determined by simulating a 1 mm beam incident on the lateral surface of an anthropomorphic head phantom and a 20 cm thick PMMA block phantom. The backscatter PSF's for the head phantom and PMMA phantom are curve fit with a Lorentzian function after being normalized to the primary dose intensity (PSF_n). PSF_n is convolved with the primary dose distribution to generate the scatter dose distribution, which is added to the primary to obtain the total dose distribution. The backscatter convolution technique is incorporated in the dose tracking system (DTS), which tracks skin dose during fluoroscopic procedures and provides a color map of the dose distribution on a 3D patient graphic model. A convolution technique is developed for the backscatter dose determination for the non-uniformly spaced graphic-model surface vertices. A Gafchromic film validation was performed for shaped x-ray beams generated with an ROI attenuator and with two compensation filters inserted into the field. The total dose distribution calculated by the backscatter convolution technique closely agreed with that measured with the film.

Keywords

dose; ROI attenuator; compensation filter; EGS*nrc*; point spread function; backscatter

1. INTRODUCTION

Fluoroscopically guided interventions can result in a significant exposure to the patient's skin, with a substantial component arising from the backscattered radiation.[1] Backscatter

factors have been measured and reported by a number of investigators for various conditions and haves been used to convert incident air kerma to the entrance skin dose at the center of the uniform field of a given field size.[2–4] However, the backscatter distribution is not uniform across the entire field, but decreases towards the edge of the field and extends beyond the collimation.[5] Moreover a single backscatter factor is not sufficient to describe the backscatter variation across the entire field, when the primary dose distribution is not uniform. X-ray field shaping devices like region of interest (ROI) beam attenuators and compensation filters modify the photon fluence in the field of view by attenuating the primary $\times$ rays outside the region of interest. ROI attenuators used for dose reduction and compensation filters used for intensity equalization reduce the entrance skin dose and modulate the spatial backscatter scatter distribution in the FOV.[6–10] Backscatter spreads from the point of primary interaction and the spatial distribution of backscatter from the patient varies in relation to the location of the ROI and compensation attenuators in beam.[11] We propose a method for the estimation and automatic mapping of cumulative skin dose for spatially shaped x-ray fields through the convolution of a backscatter to primary point-spread function (PSF_n) with the primary dose distribution.[12] The new mode of dose calculation is integrated with our skin dose tracking system (DTS), a software code that automatically calculates the entrance skin dose for fluoroscopic interventions and maps the dose intensity on a human graphic model using a dose-color scale.[13–20] This investigation is done using two phantom models and several distinctly shaped beams to substantiate the accuracy of the proposed dose calculation technique.

2. METHODS AND MATERIALS

A normalized backscatter point spread function is determined using EGS*nrc* Monte-Carlo by simulating a 1 mm pencil beam incident on a PMMA phantom and an anthropomorphic head phantom.[21–24] The spatial distribution of backscatter is calculated through the convolution of PSF*n* over the primary dose distribution. Two shaped fields are generated using ROI beam attenuators and compensation filters over the phantoms and the dose distribution determined through the convolution is validated with Gafchromic film. Figure 1 illustrates the backscatter PSF*n* convolution method. In this example, the backscatter is seen to peak at the center of the field and extend outside the field boundary.

2.1 Region of Interest Attenuators and Compensation filters

The region of interest (ROI) attenuator used in this study consists of a copper sheet with a central aperture that can be inserted into the field using an automatic placement device. The ROI beam attenuator results in dose savings to the patient by attenuating the primary in the periphery and reducing the backscatter in the region of interest. Image quality in the region of interest is improved due to less scatter reaching the image receptor and image quality in the periphery is degraded due to noise. A noisy periphery can be clinically acceptable to the interventionalist since it may be needed only for reference.

Two of the three shaped compensation filters available in the collimation assembly of Toshiba Biplane Infinix machine are used for the current study. Compensation filters are used to offset the varying patient transmission across the field of view, to equalize the signal

that reaches the image receptor. The compensation filters used have a uniform thickness except at the edges where it tapers to nearly zero. The filters can be inserted into the field remotely and translated as well as rotated.

The transmission of the ROI attenuator and compensation filters was measured as a function of beam energy and beam filtration using a calibrated 0.6 cc Farmer type ionization chamber (model NE2507/3A, Nuclear Enterprises, Fairchild, NJ) and stored in the DTS calibration files. The DTS receives exposure and geometric parameters from the angio machine in real time through a digital CAN bus and appropriate transmission factors are chosen from the calibration files for the calculations based on these parameters. The simulated $\times$ rays in the DTS are evaluated for their intersection with the graphical outlines of ROI beam attenuator and compensation filters by means of the Moeller-Trumbore ray-triangle intersection algorithm.[25] The primary dose intensity of the rays in the unattenuated openings are unchanged and the rays intersecting the ROI attenuator and compensation filters are reduced by the transmission factor.

2.2 Backscatter PSF for PMMA phantom and entrance dose calculation

A one mm pencil beam is simulated using EGS*nrc* Monte Carlo software to be incident on a 20 cm thick PMMA phantom.[12,26] The voxel size of the PMMA EGS*nrc* model was maintained at $1 \times 1 \times 1$ mm since the design was simulated. The beam is enclosed by a single voxel and the dose intensity estimated per voxel is the average across its entire volume.

The dose profile across the x-ray beam is obtained with and without the phantom to determine the total and primary dose distributions, respectively. The primary dose distribution is subtracted from the total dose to estimate the scatter variation, which is subsequently normalized to the primary intensity. The normalized scatter dose distribution is curve fit using a Lorentzian function to obtain the backscatter to primary PSF_n as shown in figure 2(*a*). The resulting PSF_n characterizes the backscatter variation produced by the 1 mm x-ray beam on the PMMA entrance surface. The PSF_n is incorporated in DTS for convolution over the vertices of a PMMA graphic model. The coordinate vertices of the DTS PMMA model are homogeneously spaced with a 1 mm separation in correspondence with the size of the x-ray beam that was used to calculate the PSF_n. The primary dose intensities for the phantom model coordinate vertices are estimated from the DTS calibration files that contains the fluoroscopy machine exposure as a function of kVp and beam filtration. The primary dose intensity is mapped onto PMMA graphic vertices using appropriate inverse square corrections with an additional transmission correction if the ray to a PMMA model vertex intersects the ROI or compensation attenuator. The scatter spread is obtained from convolution of the backscatter PSF_n with the primary intensity around that vertex and is added to the primary dose to obtain the total dose. The aggregate dose is thus calculated for all graphic vertices and color mapped according to the DTS dose-to-color scale.

The quantitative dose accuracy of the new entrance dose calculation method was validated by comparison to the dose measured using Gafchromic ™ XR-QA2 (Ashland, NJ, USA) film. The dose-response curve of the film was determined with a 0.6 cc Farmer type ionization chamber (model NE2507/3A, Nuclear Enterprises, Fairchild, NJ).[27] Small strips

of film were placed at the entrance surface of a $30 \times 30 \times 20$ cm thick PMMA phantom and exposed to a varying number of digital acquisition frames (80 kVp, 15f/s, with 1.8 mm Al beam filtration). The dose to the film for each exposure was determined by placing the ion chamber at the location of the film and the charge was measured using a PTW UNIDOS dosemeter. The exposed film was scanned and the red channel was read using ImageJ 1.48v software (National Institute of Health, USA) and its value plotted to obtain the calibration curve.

Two shaped FOV's are made using the ROI attenuator and compensation filters inserted into the x-ray field and the PMMA phantom was exposed with a sheet of Gafchromic film placed at the entrance surface. A line dose profile was obtained along the midline of the field from a scan of the Gafchromic film, perpendicular to the anode-cathode direction. A surface dose mapping was performed simultaneously by DTS software with the PSFn convolution technique using the exposure and geometric parameters obtained from the angio-machine through a digital CAN bus. The DTS-calculated dose intensities were compared to those determined from the Gafchromic film.

2.3 Backscatter PSF for SK -150 head phantom and entrance dose calculation

A CT DICOM file of the SK-150 phantom was converted to a compactable. egsphant file to simulate the phantom model in EGS Monte Carlo software. The voxel size of the. egsphant CT file was maintained at 1 mm which was the resolution of the CT scan voxels. A one mm square 80 kVp x-ray beam was generated in EGS and was incident on the lateral surface of the head phantom. The location was chosen due to the predominance of vasculatures and a common projection for neuro imaging. The backscatter PSF is determined subsequently using the same method as used for PMMA described in Section 2.2 and is shown in figure 2(b).

An appropriate SK-150 head phantom model is selected from the DTS graphic library. Unlike the PMMA phantom model, the SK head phantom model is comprised of vertices with a non-uniform spatial distribution of coordinates analogous to a 3D graphic mesh. The dose measurement is performed by placing Gafchromic film over the nearly flat lateral surface of the SK-150 head phantom. Since the convolution requires a matrix of elements uniformly spaced at 1 mm, a flat surface of uniformly space vertices was created for the entrance field. The primary dose distribution was calculated for the head model coordinates in the entrance field of view, and the PSFn convolution and backscatter determination was performed on the flat surface.

The dose profile for two nonuniform x-ray beams projected on the lateral surface of the SK-150 head phantom was validated using Gafchromic film. Two modulated x-ray beam distributions are produced using the ROI attenuator and two compensation filters. The x-ray fields are projected onto the phantom and the dose was simultaneously calculated using the convolution method in DTS and measured using Gafchromic film.

3. RESULTS AND DISCUSSIONS

The backscatter PSF_n's generated for the 20 cm thick PMMA and SK–150 phantoms are curve fit with a Lorentzian as shown in figure 2(*a*) and 2(*b*). The PSF*n* for the SK-150 head phantom is specific to the region of exposure due to the internal anatomic structures. The magnitude of the peak scatter for the SK-150 phantom is observed to be less than the PMMA (0.0066 and 0.0081, respectively), most likely due to the absorption of backscatter by bone under the skin and the higher density of the PMMA.[3, 28] The validation results of figures 3b, 4b, 5b, and 6b show the scanned profiles for Gafchromic film measurements with the error bars representing plus and minus two standard deviations resulting from uncertainty in the dose-response curve.

3.1 PMMA Phantom

The PSF convolution technique for skin dose estimation is validated by means of Gafchromic XR-QA2 films placed at the entrance surface of 20 cm thick PMMA for two different non-uniform x-ray fields generated using beam shaping devices. The x-ray field was incident on the PMMA phantom laterally to avoid the forward scatter from patient table. The ROI attenuator and compensation filters were inserted into the central part of the FOV as it might be for a clinical procedure. The entrance area not covered by the attenuators received higher dose in the FOV and the area shadowed by the attenuators received relatively low dose due to the low primary transmission with much of the scatter dose originating from the uncovered region. The DTS color dose mapping on the PMMA model with an ROI inserted in the field and the line-dose profile comparisons are illustrated in figures 3(*a*) and 3(b). The color dose scale shown in figure 3(a) ranges from 0 – 100 mGy. The line dose intensity profile obtained from the film is normalized to the primary dose at the center of the ROI as shown in figure 3(b). The entrance FOV was maintained at 15×15 cm. The PSF convolution method accurately calculates the entrance skin dose in the unattenuated region of interest within 2.5 % of that measured using the Gafchromic film. The unattenuated circular region of interest receives 20 % backscatter to primary as shown in figure 3(b), whereas, in the attenuated periphery, the backscatter to primary ratio ranges from 1.25 to 0.25.

Skin dose calculation while using compensation filters has been reported previously by us,[10] and there was a discrepancy between the Gafchromic film measurement and DTS calculation in the attenuated periphery, since the backscatter dose component was not accounted for in the calculation. Figures 4(a) illustrates the DTS color dose distribution calculated using the backscatter PSF*n* convolution technique for the PMMA graphic with the two compensation filter outlines, and figure 4(b) shows the corresponding line-dose profile comparisons between the Gafchromic film and DTS.

The dose in the unattenuated region calculated by PSFn convolution agreed within 3 % of that measured with the Gafchromic film. In the attenuated region, the dose is calculated within 17 % of that of the Gafchromic film, due to the larger film uncertainty in the low dose range.

3.2 SK-150 Phantom

Figure 5(a) illustrates the color-coded dose mapping on a DTS head model equivalent to the SK-150 head phantom for the ROI attenuator at the center of the x-ray field. The line dose intensity profile through the center of the FOV is determined from the DTS head model and Gafchromic film and the comparison is shown in Fig. 5(b). The skin dose obtained from the convolution and film is normalized with the primary dose intensity at the center of the region of interest. The backscatter to primary ratio in the unattenuated ROI determined by the convolution is within 3 % of that of the Gafchromic film. In the attenuated periphery, the backscatter to primary ratio drops from 0.5 to 0.06 going outward. The relatively lower backscatter dose compared with that of PMMA is due to the smaller field size and scatter absorption by the bone in the phantom as well as higher density of the PMMA.[3, 28]

The film and DTS dose is also compared for a non-uniform x-ray field generated using two compensation filters. A non-uniform FOV with two compensation filters is projected over the lateral surface of the SK-150 phantom and the dose determined by means of DTS and film. Figure 6(a) shows the DTS dose map with two compensation filter outlines over a head model equivalent to the SK-150 head phantom. Figure 6(b) displays the DTS and film dose profile comparison where the profiles are normalized to the unattenuated primary dose in the unattenuated center. The relative dose calculated using the convolution in the unattenuated central region agreed within 3 % of that measured with the film.

4. CONCLUSIONS

The calculation and mapping of the spatial backscatter spread due to non-uniformities in the x-ray field are necessary to obtain an accurate determination of the skin dose distribution. The usefulness of a backscatter point spread function to estimate the backscatter distribution over the skin, particularly for shaped x-ray fields generated using ROI beam attenuators and compensation filters is investigated. The backscatter point spread function convolved over the primary dose distribution generates the backscatter distribution, which is subsequently added to the primary dose distribution to generate the total skin dose distribution. This method was validated with Gafchromic film for homogenous and non-homogenous phantoms. The backscatter PSF convolution technique is a unique solution to the problem of estimating the entrance skin dose in the presence of inhomogeneities in the x-ray beam and could serve as a fast, accurate method to determine the backscatter distribution for x-ray fields generated during fluoroscopically guided interventions.

Acknowledgments

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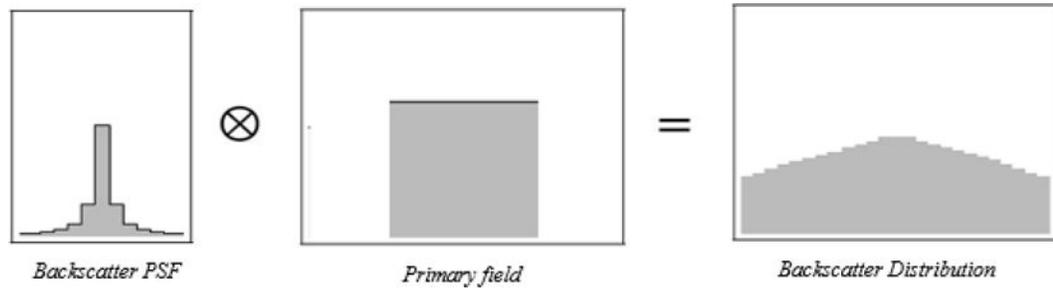
Fig. 1.
Illustration of the convolution of the backscatter point spread function with the primary dose distribution to generate the backscatter distribution.
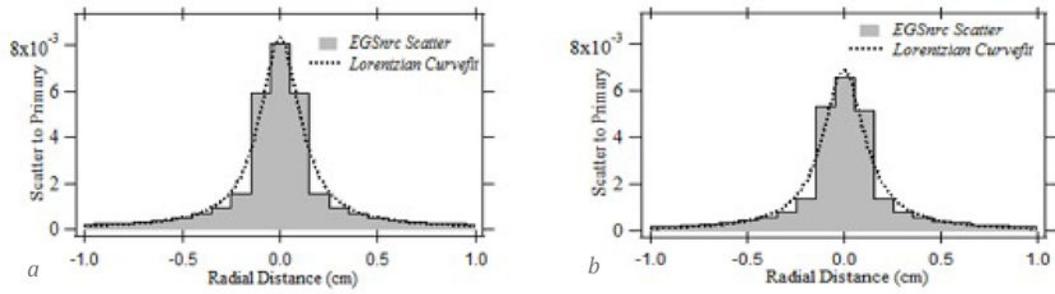
Fig. 2.
Normalized Backscatter PSF_n with Lorentzian curve fit for (**a**) flat PMMA phantom and (**b**) SK-150 head phantom.
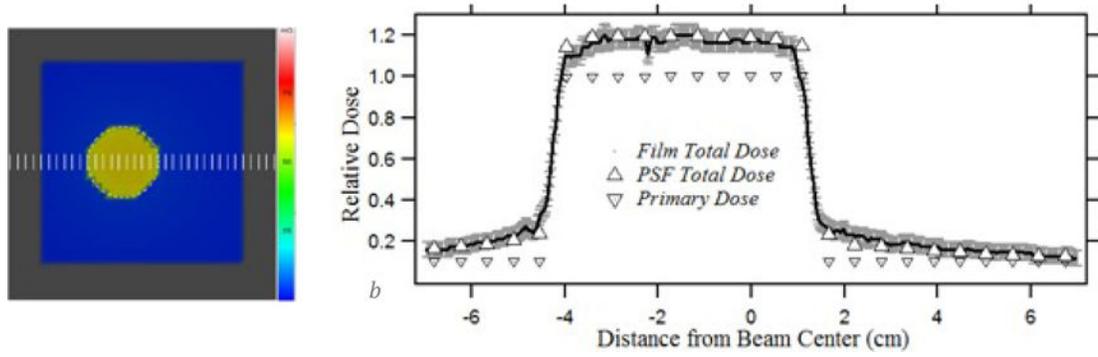
Fig. 3.
Entrance dose for PMMA phantom with off-centered ROI attenuator in the FOV (*a*) DTS display of dose distribution on a PMMA block graphic model (**b**) line profile comparison between film and PSF convolution results.
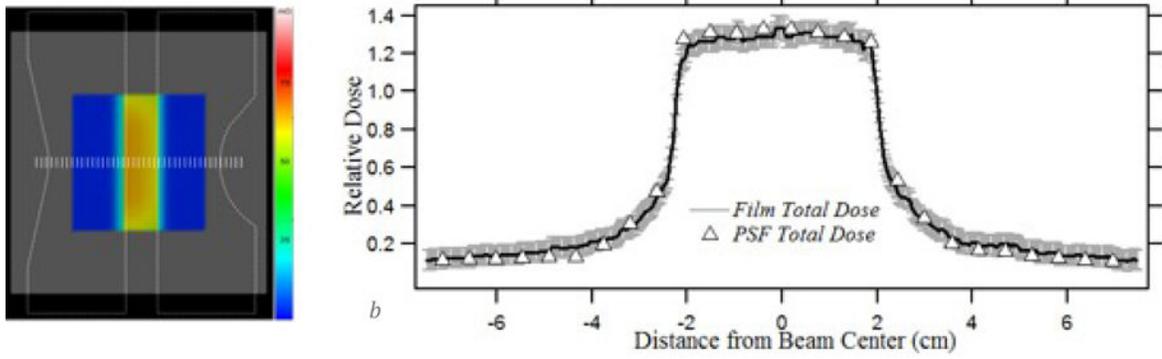
Fig. 4.
Entrance dose for PMMA phantom with two compensation filters (*a*) DTS display of dose distribution on a PMMA block graphic model with compensation filter outlines (**b**) line profile comparison between film and PSF convolution results,
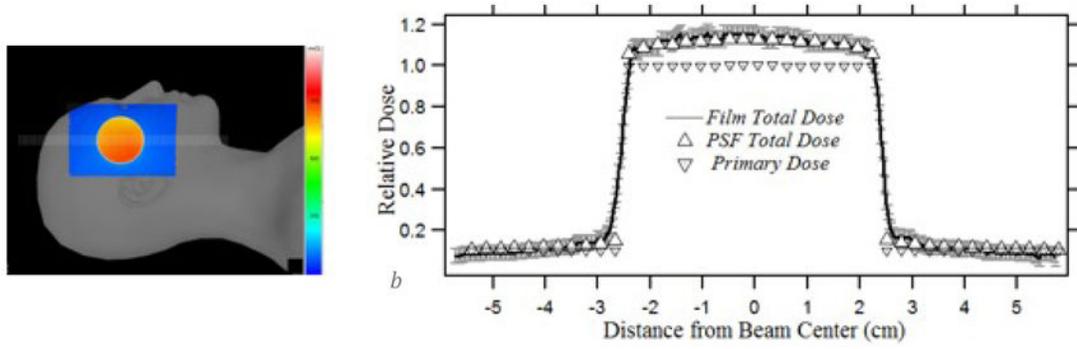
Fig. 5.
Dose with ROI attenuator in the beam for the SK-150 phantom: **(a)** DTS color dose mapping on a head phantom model and **(b)** DTS and film dose profile comparison
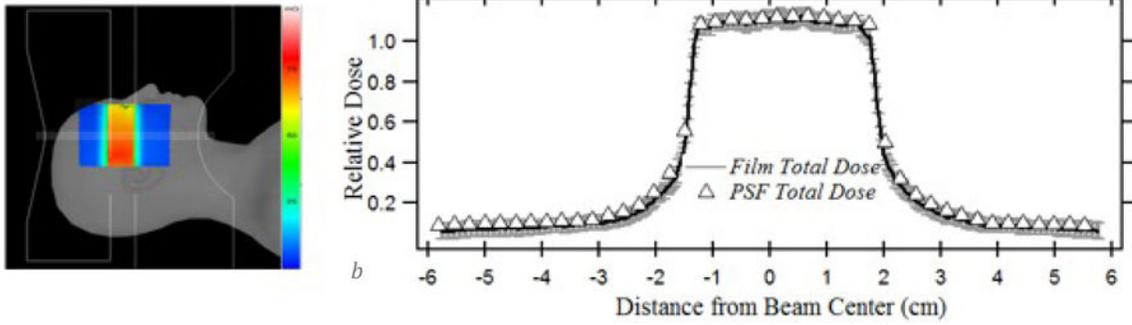
Fig. 6.
Dose for the SK-150 head phantom with two opposed compensation filters and an unattenuated region in the center of the FOV. **(a)** Screenshot of the DTS head model showing the color-coded dose mapping after exposure **(b)** Comparison of the dose profiles calculated using the backscatter convolution technique and measured with Gafchromic film.