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Incorporating Corrections for the Head-Holder and Compensation Filter when Calculating Skin Dose during Fluoroscopically-Guided Interventions

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Abstract

The skin dose tracking system (DTS) that we developed provides a color-coded illustration of the cumulative skin dose distribution on a 3D graphic of the patient during fluoroscopic procedures for immediate feedback to the interventionist. To improve the accuracy of dose calculation, we now have incorporated two additional important corrections (1) for the holder used to immobilize the head in neuro-interventions and (2) for the built-in compensation filters used for beam equalization. Both devices have been modeled in the DTS software so that beam intensity corrections can be made. The head-holder is modeled as two concentric hemi-cylindrical surfaces such that the path length between those surfaces can be determined for rays to individual points on the skin surface. The head-holder on the imaging system we used was measured to attenuate the primary x-rays by 10 to 20% for normal incidence, and up to 40% at non-normal incidence. In addition, three compensation filters of different shape are built into the collimator apparatus and were measured to have attenuation factors ranging from 58% to 99%, depending on kVp and beam filtration. These filters can translate and rotate in the beam and their motion is tracked by the DTS using the digital signal from the imaging system. When it is determined that a ray to a given point on the skin passes through the compensation filter, the appropriate attenuation correction is applied. These corrections have been successfully incorporated in the DTS software to provide a more accurate determination of skin dose.

Keywords

Dose tracking; Skin dose; Fluoroscopic interventional procedures; Compensation filter; Head Holder

1. INTRODUCTION

The skin dose tracking system (DTS) that we developed^{1,2} recreates the real-time interventional procedure in a 3D graphical environment with the patient simulated by a closely matching graphical model and the cumulative radiation dose received during the intervention is illustrated by a color-coded mapping as shown in Figure 1. OpenGL assisted graphical rendition is performed utilizing the geometry and exposure parameters received from the angiographic machine through a digital bus.

For neuro-interventional procedures, a head-holder is placed on the table top to support and restrain the patient's head. Since the x-ray beam passes through this holder before reaching

the patient, the patient dose is modified by attenuation. Likewise, shaped compensation filters are available on the collimator assembly that can be moved into the beam and translated or rotated to provide beam equalization; these filters can substantially reduce the patient dose over those regions of the field that they cover. Both of these devices have now been modeled in the DTS so that the skin-dose distribution can be more accurately estimated.

2. METHODS AND MATERIALS

2.1 Head-holder attenuation and scatter corrections

A head holder as shown in Figure 2(a) is a head restraining device used in neuro-interventions; the one used in this study is made of carbon fiber and has an interior soft comfortable foam. Figure 2 (b) shows the design of the head holder incorporated into the DTS graphic. The attenuation correction was determined by measuring the transmission of the holder with a 6 cc PTW ionization chamber (Type 34069, PTW, Freiburg, Germany). This correction is incorporated in the DTS by implementing a finite cylinder-ray intersection algorithm to determine the path length through the cylindrical holder.

The inner or outer surface of the head holder can be approximated as a semi-cylinder of fixed length, which can be mathematically calculated using the general finite semi-cylinder equation given by:

$$|\vec{q} - \vec{o}_a - (\vec{d}_a \cdot (\vec{q} - \vec{o}_a)) \vec{d}_a|^2 - |\vec{r}|^2 = 0, \quad \text{for } z \leq z_{max}, y_{min} \leq y \leq y_{max}$$

where $\vec{q}(x, y, z)$ is a point on the cylinder surface. $\vec{o}_a$ and $\vec{d}_a$ are the origin and the directional vectors for a line about which the cylinder is oriented and r is the radius of the cylinder. Limits on the coordinate axis y and z are imposed so the cylinder approximates the head holder dimensions. The correspondence of the variables in the above equation to the concentric cylinder geometry is illustrated in Figure 3. The coordinates in the cylindrical surface $\vec{q}(x, y, z)$ in the above expression is substituted with parametric equation of the primary ray $\vec{p}(t) = \vec{p}_0 + \vec{v}t$, where $\vec{p}_0$ is the ray origin, $\vec{v}$ is the ray directional vector and t is the ray parameter. The resulting quadratic equation is solved for ' t ' and a positive valued solution for ' t ' indicates an intersection between ray and the finite cylinder. The ' t ' value thus obtained is substituted back into the parametric ray equation to obtain the intersection point. Ray – cylinder intersection points are calculated independently for the two concentric finite semi-cylinders approximating the inner and outer surfaces of the head holder. The distance between two intersecting points by the same ray yields the thickness of the head holder encountered by that ray.

The head-holder used on this imaging system is placed on the patient table which provides additional attenuation and the table and pad attenuation was similarly measured and a correction applied that is a function of the ray angle through the table and pad.³

Attenuation factors for rays at normal incidence to the head holder as well as for the table plus pad are saved in a calibration file for each beam filter as a function of kVp. For

obliquely incident x-rays a correction factor is applied based on the additional calculated holder thickness above the thickness for a normal ray. To account for the forward scatter by the head holder, correction factors are determined by measuring the exposure with an ionization chamber placed at the entrance surface of a skull phantom positioned within the holder, as a function of entrance beam size for various beam filters and kVps. For dose calculation, the appropriate factor is chosen from the file and applied for the machine parameters being used for that particular exposure.

2.2 Compensation filter attenuation and scatter correction

Three built-in compensation filters whose shape is shown in Figure 4 are used to equalize intensity changes in the field of view and compensate for varying body thickness. All filters have the same uniform thickness except at the edges where the thickness tapers to zero. The shapes of these three filters are modeled in the DTS and the system tracks their movement in the x-ray field in real-time by reading signals on the imaging system digital bus. The attenuation through the filters was measured with an ionization chamber as a function of kVp and beam filter. This measurement provides correction factors for those rays which pass through the compensation filters.

3. RESULTS AND DISCUSSION

3.1 Head Holder Correction Results

Figure 5(a) shows the attenuation correction factor for the x - rays at zero degrees to the surface normal of the head-holder. The attenuation varies from 15 – 20 % for 50 kVp to 10 – 15 % for 120 kVp. Due to the curvature of the holder, the rays passing through the periphery have a path length over 3.5 times the shortest path length normal to the surface resulting in 40 - 45% attenuation. Figure 5 (b) shows the calculated variation of attenuation with divergence angle relative to the central ray for the plane perpendicular to cylindrical axis for an 80 kVp, 0.2 mm Cu filter x- ray beam . Oblique rays outside of this plane may have even longer path lengths and even higher ray attenuation. The 3D paths lengths are calculated by the software and used for attenuation correction.

The DTS uses the premeasured attenuation factors for the primary ray normal to the surface and applies an additional correction for obliquely incident rays. These corrections for the head holder were incorporated into the DTS software and evaluated for its accuracy during dose calculations. Figure 6 a and b shows the difference in the color coded dose distribution obtained by the DTS with and without the head holder being used for two identical simulated interventions. The color disparity between the two graphics indicates the differences in dose received by the patient head due to primary ray attenuation by the head holder in accordance with the DTS dose-to-color conversion. We performed a quantitative validation of the DTS correction for the head holder using Gafchromic® film (XR-RV3, International Specialty Products Corporation, Advanced Materials Group, Wayne, NJ). The radiochromic film was positioned between a 16 cm diameter PMMA cylindrical phantom and the head holder and the 2D dose distribution was recorded. The density on the film was converted to dose using a calibration curve derived from exposure of the film to known values of dose. ⁴

Fig. 7 gives the ratio of DTS calculated dose to the dose measured with the Gafchromic film for locations around the circumference of the cylindrical phantom. The center of the head holder was at the 8 cm position. The DTS dose is seen to agree with the dose values indicated by the exposed film within $\pm 2\%$, indicating proper functioning of the head holder correction.

3.2 Compensation filter correction results

Attenuation correction for the three compensation filters has been added to the DTS software with the capability to track their movements in real time. Figure 8 shows the measured attenuation corrections for the compensation filter for all angio-machine beam filters; it is seen that the compensation filter attenuation varies from 99 % to 97 % at 50 kVp and 78 to 58 % at 120 kVp. Compensation filter corrections are incorporated within the DTS software with matching filter shape outlines and include the edge taper. Fig. 9 shows the dose distribution on DTS patient graphics with each of the three compensation filters placed in the center of the beam. The lighter blue color corresponds to the decreased attenuation at the tapered edge of the compensation filter.

The compensation filter correction for the DTS software was validated using radiochromic film. The film was placed on the patient table under a 20 cm thick block of PMMA and opposed compensation filters were partially inserted into the beam so that there was a central separation between them as seen in Fig 10. A graphic model of this block was used for the “patient” in the DTS and the dose distribution was calculated with the filter correction for a single exposure sequence. Figure 11 compares DTS and Gafchromic dose profiles for a line passing through both filters and the central unattenuated region. The higher plateau in the graph is the area with un-attenuated dose and regions on both sides have attenuated dose due to the compensation filters, with a graduated dose where the filter thickness is tapered. The higher value of measured dose under the filter is likely due to backscattered radiation from the unattenuated region which is not accounted for in the calculation.⁵ Correction for scatter is under investigation and will be implemented in future software updates.

4. CONCLUSIONS

We have successfully integrated corrections for the head holder and compensation filters in the DTS to provide increased accuracy in skin-dose distribution determination and validated the numerically calculated dose accuracy by means of measurements with radiochromic film.

5. ACKNOWLEDGMENTS

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Fig. 1. Display screen of DTS illustrating the color-coded dose distribution on an adult patient graphic for a simulated fluoroscopically guided intervention.

Fig. 2. (a).
Picture of the head holder used for neuro-interventions positioned on the patient table.

Fig. 2. (b).
Design of the head holder incorporated with the Dose Tracking System graphic display.

Fig. 3. Concentric finite cylinders approximated to the head holder inner and outer surfaces, with directional vector $\vec{d}_a$, cylinder origin $\vec{o}_a$ and coordinate bounds z_{const} , y_{max} and y_{min}

Fig. 4.

Photos of the control room monitor display showing the outline of each of the three compensation filter designs with the outer edges represented by the solid lines on the virtual collimation display on a last image hold (LIH) frame. Here the filters are centered in the field, but each filter can be independently moved to any location and orientation in the field.

5 a.

Head-holder attenuation correction factor measured for range of kVp's for four filters in the fluoroscopy machine.

Fig. 5 b.
Attenuation of an individual ray through head holder as a function of ray divergence angle relative to the central ray (80 kVp, 2 mm Cu).

Fig. 6. DTS color-coded dose representation for a patient head a) with the head holder in use and b) without the head holder.

Fig. 7.

The ratio of DTS calculated dose to the dose measured with Gafchromic film at corresponding locations on the cylindrical phantom.

Fig. 8.
Attenuation correction factor measured for a compensation filter as a function of kVp for the four different beam filters in the tube.

Fig. 9. Dose distribution on a patient graphic for a beam attenuated by a) compensation filter one, (b) compensation filter two and c) compensation filter three. The filters are centered in the beam and the intensity variation of the dose near the filter edges occurs due to the tapered thickness.

Fig. 10. PMMA block graphic model with opposite compensation filters partially deployed in to the beam. This set up is used for the filter correction performance validation.

Fig. 11.

(a) DTS calculated dose profile (red data points) between two compensation filters compared to the dose profile measured with Gafchromic film (blue data points). (b) DTS display of dose distribution for two opposed compensation filters arranged as might be for a cardiac procedure to reduce the intensity from the surrounding lung field.