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A system to track skin dose for neuro-interventional cone-beam computed tomography (CBCT)

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Abstract

The skin-dose tracking system (DTS) provides a color-coded illustration of the cumulative skin-dose distribution on a closely-matching 3D graphic of the patient during fluoroscopic interventions in real-time for immediate feedback to the interventionist. The skin-dose tracking utility of DTS has been extended to include cone-beam computed tomography (CBCT) of neurointerventions. While the DTS was developed to track the entrance skin dose including backscatter, a significant part of the dose in CBCT is contributed by exit primary radiation and scatter due to the many overlapping projections during the rotational scan. The variation of backscatter inside and outside the collimated beam was measured with radiochromic film and a curve was fit to obtain a scatter spread function that could be applied in the DTS. Likewise, the exit dose distribution was measured with radiochromic film for a single projection and a correction factor was determined as a function of path length through the head. Both of these sources of skin dose are added for every projection in the CBCT scan to obtain a total dose mapping over the patient graphic. Results show the backscatter to follow a sigmoidal falloff near the edge of the beam, extending outside the beam as far as 8 cm. The exit dose measured for a cylindrical CTDI phantom was nearly 10 % of the entrance peak skin dose for the central ray. The dose mapping performed by the DTS for a CBCT scan was compared to that measured with radiochromic film and a CTDI-head phantom with good agreement.

1. INTRODUCTION

The skin dose tracking system (DTS) ¹ recreates the real-time fluoroscopic interventional procedure in a 3D graphical environment with the patient simulated with a closely matching 3D model (Figure 1). The cumulative radiation dose² received during the procedure is illustrated by a color-coded representation. OpenGL assisted graphical rendition is performed utilizing the technique and geometric parameters from the angio machine received through a digital CAN bus. DTS contains an extensive collection of distinct patient models of various size and shape for optimal matching to the patient.

Rotational angiography has been a very effective tool for 3D reconstruction on clinical C-arm gantry systems. These systems make use of either x-ray image intensifiers (XII) or flat panel detectors (FPD) and have the capability to perform both fluoroscopy and 3D volume reconstruction. CBCT imaging modality is increasingly used for dental and orthodontic procedures and has replaced lateral cephalograms and panoramic images, but there have been recommendations to limit its use due to the radiation risks.³⁻⁴ A large FOV CBCT delivers skin dose ranging between 55 – 277 μ Sv across various dental protocols⁵. In

addition, CBCT is being used during interventional vascular fluoroscopic procedures including in neuroradiology.^{6,7} The CBCT skin dose and the dose to the lens of the eyes delivered during the procedure arises from the primary dose, scattered radiation inside and outside the x ray field, and the transmitted dose on the exit x-ray field. The x ray source rotation around the patient causes the dose distribution to the regions that are not directly exposed to the primary unattenuated x-ray field and thus there is a dose spread around the complete object being imaged. All of these sources of radiation have been incorporated into the DTS software so that the skin dose for CBCT can be accurately estimated.

2. MATERIALS AND METHODS

For a single x ray projection in CBCT, the patient skin on the entrance x ray field receives the dose arising from the primary x ray beam and the patient backscatter. The backscatter received by the patient skin falls gradually from the center of the field to the x ray field edge and spreads outside the beam beyond the collimation. Multiple projections of the beam around the imaged object accumulate the scatter dose so that it can become a significant dose contributor. Conventional DTS computes the patient entrance skin dose by determining the primary dose and various scatter dose elements present within the collimation. For DTS to be enabled for CBCT, the evaluation of skin dose outside the x ray field needs to be understood. The scatter spread outside the collimator edge was measured using radio chromic film. A 20 cm thick PMMA Lucite phantom was placed on top of the table with a radio chromic film placed on the entrance surface as shown in figure 2. The exposure was made laterally with the collimator deployed partially blocking the beam. Figure 2a illustrates the schematics of the complete experimental setup. The scatter peaks at the center of the partially open x ray beam and drops gradually outside the collimator. The primary dose spread inside the beam and outside the collimator, if any, was measured without the patient backscatter as indicated in figure 2b. The experimental setup remains unchanged from figure 2a except the removal of the patient phantom

The primary dose profile obtained from the Gafchromic film was subtracted from the total dose profile to obtain the scatter alone distribution. The spatial scatter spread was curve fitted with the best fit being a sigmoid curve. The resultant scatter profile is incorporated into the DTS enabling the estimation of scatter dose spread inside and outside the entrance x ray field.

Dose on the exit part of x ray field resulting from the transmitted ray (primary and scatter) constitutes another major component of the patient skin dose in CBCT. For CBCT DTS, an accurate tracking of the skin dose is possible with a determination of the ray specific entrance dose and exit dose elements. The exit x ray field dose profile due to the transmitted rays was studied using radiochromic film. The schematics of the experimental setup is shown in figure 3

A CTDI cylindrical head phantom was covered with radiochromic film on both entrance and exit sides and exposed to a single projection of x rays; and the dose measured by the film on the exit x-ray field side is dependent on the path length of the ray through the cylindrical phantom and includes the attenuated primary and the scatter reaching the exit field side.

3. RESULT

Figure 4a indicates the results of the scatter spread study inside and beyond the collimator edge outside the x ray field acquired using radiochromic film. The upper graph contains the total dose variation inside the x ray field and beyond the collimator edge with the PMMA block phantom positioned in the beam, thereby including the back scatter and the primary dose. The lower curve in Figure 5a contains the primary dose profile across the same spatial domain obtained without the phantom. The primary dose is subtracted from the total dose to obtain the spatial scatter variation. Figure 4b indicates the spatial scatter profile normalised to the peak scatter value. The scatter exposure spreads out after the collimator edge to approximately 7–8 cms.

The scatter dose variation inside the beam and scatter dose spread outside the collimator is included in the skin dose calculation performed by DTS. The scatter dose outside the collimated x-ray field adds up over various projections due to the gantry rotation and accounts for an important dose component received by the patient skin.

Figure 5 shows the dose on the exit side of the x ray field due to the transmitted ray. In the figure, the dose intensity indicated at the exit side of the x ray field for the individual rays is that value after extrapolation by inverse-square to the point of entry for that specific ray through the cylindrical phantom, so that the curve includes the effect of “broad-beam” attenuation only and not distance; this value is plotted as a function of the ray length intersecting the cylindrical phantom. The dose values in the graph are normalized to the highest entrance skin dose value.

The curve fit obtained from the data points are added to DTS. The exit intersection point on the cylinder graphics for a specific x ray is located and the corresponding entrance skin dose magnitude is modified for the inverse square distance equivalent to the x ray intersection length with the cylinder model. The ray specific exit dose is calculated for the cylinder graphic vertices lying on the exit half of the beam and is color mapped in the DTS display using the dose – color scale conversion corresponding to the exit dose magnitude. With the gantry and thereby the x-ray field rotation, the patient graphic vertices change the orientation of their normal vectors for the entrance x-ray field and exit x-ray field. The cumulative surface dose on the patient graphic vertices due to the primary, multiple scatter contributions, and ray transmission are estimated and color mapped for the dose illustration.

The DTS calculates the skin dose for CBCT taking into account these corrections. The agreement of the dose mapping determined by the DTS with the actual distribution was verified by means of a Gafchromic® film (XR-RV3, International Specialty Products Corporation, Advanced Materials Group, Wayne, NJ) and a cylindrical CT phantom. Figure 6 indicates the experimental setup with the CTDI phantom placed on the table for a CBCT scan. For this study, a standard flat panel detector was used with a 12 inch FOV with an SID of 120 cm and the 16 cm diameter CTDI phantom was placed at the isocenter of the C-arm system. The curved surface of the cylinder phantom was covered with the film and the phantom was placed on the table top in the same orientation as a patient head during the

CBCT scan. Six rounds of CBCT scans were performed with the same sheet of film to provide an exposure within the range of the Gafchromic film.

Each individual CBCT scan had an initial fluoroscopy exposure made with AP and lateral projections for “patient” positioning followed by a digital angiography test shot (DA) to determine the appropriate x-ray parameter for optimum image quality. The following table gives the exposure parameters used for the CBCT scans in the present study.

	kVp	Tube Current (mA)	Pulse Width (ms)	Beam Filtration
Fluoroscopy	80	80.2	9.93	0.5 mm Cu
DA Test Shot	80	627	3.69	1.8 mm Al
DA for 3D reconstruction	80	627	3.69	1.8 mm Al

The dose distribution across the phantom surface is recorded on the Gafchromic film and the density of scanned film is converted to dose using a calibration curve derived from the exposure of the film to known values of dose⁶.

The graph of Figure 7c shows the dose distribution profiles from a simulated CBCT procedure determined from the Gafchromic film, from the skin dose tracking system without the CBCT corrections and from the DTS with the necessary CBCT corrections incorporated. In figure 7c, the CBCT-corrected DTS curve is noticeably higher in magnitude compared to the uncorrected DTS curve; however, the corrected DTS curve is in good agreement with the Gafchromic film measured dose values except at left and right anterior oblique view angles (LAO/RAO) greater than about 145 degrees. This difference is likely due to a difference in the patient table height and thus the phantom position in the DTS compared to in the measurement.

5. CONCLUSIONS

The dose tracking system has been modified to enable accurate skin dose mapping for Cone Beam Computed Tomography procedures. This mapping can be combined with the real-time mapping obtained with the DTS for a subsequent fluoroscopically-guided interventional procedure to obtain the total dose distribution.

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

Figure 2.

a.) The experimental setup for the measurement of the primary plus backscatter dose distribution using radio chromic film with a partially deployed collimator. **b.)** The experimental set up for the primary dose distribution measurement using radio chromic film for a beam with a partially deployed collimator. The patient phantom was removed to obtain the dose profile without backscatter.

Figure 3.
The experimental setup for the transmitted dose measurement using radiochromic film wrapped around the phantom.

Figure 4.

a.) The total dose profile and the primary dose profile measured using a radio chromic film across the collimator edge. **b.)** The primary dose profile is subtracted from the total dose profile leaving the scatter variation across the collimator

Figure 5.

The exit dose profile of the cylindrical CT phantom for a single projection measured using a radiochromic film. The dose values are normalized to the peak entrance skin dose value for the frontal projection.

Figure 6.

a) The experimental set up for the validation with Gafchromic film **b)** The 16 cm diameter CTDI PMMA Phantom that is covered with the Gafchromic film and is placed on the patient table. The projection images were acquired at an interval of 2 degrees for a rotational protocol that began at 103^0 left anterior oblique angle and finished at 103^0 right anterior oblique angle.

Figure 7.

a) The color mapping of dose for the CBCT scan of the PMMA Phantom depiction in the DTS display with the color – code indicated in the bar on the right. **b)** the 16 cm CTDI PMMA phantom with the LAO/RAO angles labelled at respective positions associated with the x axis of the validation curves in the graph; **c)** the validation dose curves for the Gafchromic film, DTS with CBCT corrections and standard DTS as used for fluoroscopy without corrections.