Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2012 February 23; 8313: 83131N-. doi:10.1117/12.911528.

Significance of Including Field Non-Uniformities Such as the Heel Effect and Beam Scatter in the Determination of the Skin Dose Distribution during Interventional Fluoroscopic Procedures

Vijay Rana^{*}, Kamaljit Gill, Stephen Rudin, and Daniel R. Bednarek

Department of Physiology and Biophysics, Toshiba Stroke Research Center, University at Buffalo (State University of New York), 3435 Main St., Buffalo, NY USA 14214

Abstract

The current version of the real-time skin-dose-tracking system (DTS) we have developed assumes the exposure is contained within the collimated beam and is uniform except for inverse-square variation. This study investigates the significance of factors that contribute to beam non-uniformity such as the heel effect and backscatter from the patient to areas of the skin inside and outside the collimated beam. Dose-calibrated Gafchromic film (XR-RV3, ISP) was placed in the beam in the plane of the patient table at a position 15 cm tube-side of isocenter on a Toshiba Infinix C-Arm system. Separate exposures were made with the film in contact with a block of 20-cm solid water providing backscatter and with the film suspended in air without backscatter, both with and without the table in the beam. The film was scanned to obtain dose profiles and comparison of the profiles for the various conditions allowed a determination of field non-uniformity and backscatter contribution. With the solid-water phantom and with the collimator opened completely for the 20-cm mode, the dose profile decreased by about 40% on the anode side of the field. Backscatter falloff at the beam edge was about 10% from the center and extra-beam backscatter decreased slowly with distance from the field, being about 3% of the beam maximum at 6 cm from the edge. Determination of the magnitude of these factors will allow them to be included in the skin-dose-distribution calculation and should provide a more accurate determination of peak-skin dose for the DTS.

Keywords

Interventional fluoroscopic procedures; Dose tracking system; Gafchromic film (XR-RV3; ISP); Skin dose; Backscatter; Heel effect

1. INTRODUCTION

X-ray fluoroscopic interventional procedures are a significant source of radiation exposure to patients and the skin is the organ receiving the highest radiation dose, being the entrance

surface. Patient skin dose resulting from these procedures has the potential to exceed threshold doses for deterministic effects such as erythema and epilation.¹⁻⁴ In interventional procedures the skin dose is accumulated at each location on the patient surface depending on the beam intensity and the duration of exposure at that location. The beam is typically moved to provide different projection views of the volume of interest during the course of a procedure and the accumulation of dose to each point has to be tracked individually to get a true representation of the dose distribution. We have developed a dose tracking system (DTS)^{5, 6} that provides a real-time mapping of the patient skin dose by software calculation of the intersection of the x-ray beam with a patient graphic and using the technique parameters and exposure geometry to determine the beam intensity at each point. The current DTS assumes that the beam is uniform in intensity and is bounded exactly by the collimators. However, we know that the beam from an x-ray tube is nonuniform due to the heel effect (i.e., x-ray intensity at the anode side is reduced compared to the cathode side of the field due to attenuation in the target material) and that backscatter from the patient can vary between points inside and outside the beam. These factors may have a significant effect on the cumulative dose distribution to the patient's skin especially in areas of beam overlap when it is moved for different CRA/CAU and LAO/RAO projections. Therefore, to determine the significance of these factors for accurate calculation of the skin dose distribution, we measured the variation of the beam in the anode cathode direction as well as the variation of backscatter from a phantom using radiochromic film. This paper reports on measurements of detailed dose profiles of the beam to evaluate these factors for possible inclusion in our DTS software.

2. MATERIAL AND METHODS

2.1 Dose Tracking System

The DTS determines the projection of the x-ray beam onto the patient by a graphic modeling of the imaging system and patient. The display gives a color-coded graphic representation of the cumulative skin dose distribution on the patient as well as the real-time dose rate and cumulative dose values at the current beam location. Figure 1 gives an example of the display during a cardiac catheterization procedure. We have previously shown that the dose calculation is accurate to within 5% at the field center.⁷

The size of the beam and its projection on the patient is obtained from the collimator position and the position of the patient relative to the x-ray tube. All information relating to the system gantry, collimator, patient table and exposure parameters is obtained from a CAN bus which runs between the components of the Toshiba Infinix C-Arm imaging system. This C-Arm system is installed in a hospital cardiac catheterization laboratory and uses a Varian PaxScan 2020 flat panel detector (FPD) with a 20×20 cm field of view. The DTS skin dose rate values are calculated from the product of the mA, pulse width, pulse rate and the mGy per mAs value which is read from a data file that contains this value as a function of kVp and filter. Cumulative dose is calculated by measuring the exposure time in intervals, multiplying it by the dose rate value and summing the result. This is done for each element of the patient graphic that is intersected by the x-ray beam (with individual inverse-square correction to that element) so that each element has its own cumulative value. The mGy per

mAs values in the data file are determined by measurement with a calibrated ionization chamber placed in the center of the beam on the patient tabletop under a 20 cm thick block of solid water material. This value thus includes patient backscatter and table attenuation. The calculation of skin dose in the program assumes the exposure is contained within the collimated beam and is uniform having the value measured at the center of the field.

2.2 Dose Profile Measurement

The primary beam intensity can vary in the anode-cathode direction due to the heel effect and the amount of backscatter can vary from the center to the edge of the field and scatter can expose the skin outside the field. To determine how much these factors contribute to the dose distribution over the skin, measurements were made using Gafchromic® film (XR-RV3, International Specialty Products Corporation, Advanced Materials Group, Wayne, NJ); this film increases in optical reflection density in relation to the amount of radiation dose absorbed. To obtain dose profiles, 43 cm long strips of film (see Fig. 2) were placed in the center of the beam oriented parallel and perpendicular to the anode-cathode direction of the x-ray tube, exposed to radiation to produce sufficient darkening, and the resultant density was read by scanning the film with a Canon MX310 scanner (75 DPI, color mode). Density profiles were obtained by averaging the value of the red channel for about 50 rows of pixels over the length of the strip and the density profiles were converted to dose profiles using the film calibration curve.

In order to determine the contribution of the various sources of nonuniformity, dose profile measurements were made under a number of different conditions. Dose profiles which included backscatter were obtained by placing the film directly adjacent to the entrance surface of a patient-simulating phantom consisting of a 20 cm thick, 30 × 30 cm block of solid water as shown in Figure 3. Measurements were made both with and without the patient table to simulate conditions for frontal and lateral projections and to determine the effect of table attenuation and scatter. The strips placed parallel to the anode-cathode direction provide information on the variation of exposure due to the heel effect. The strips placed perpendicular to the anode-cathode direction of the x-ray tube provide the variation of exposure due to the patient and table scatter. In all cases, the film was placed in a plane 15 cm tube side of isocenter to approximate the entrance plane of the patient, while the SID for the FPD was 100 cm. Unless indicated otherwise, exposures were made using the maximum beam size for the 20 cm mode for the FPD and at 80 kVp with 1.8 mm Al added filtration (4.14 mm Al HVL) which is the typical setting for cardiac digital acquisition on the Toshiba unit for an average patient.

2.3 Film Calibration

The film was calibrated by exposing small strips of the Gafchromic® film, placed in the center of the field at 15 cm tube side of the isocenter, to known exposure values as measured with a calibrated 15 cc pancake ionization chamber (Model 96035B, Keithley Instruments, Cleveland OH). The reflection density over the exposed area of the film was scanned with a Canon MX310 flatbed scanner (75 DPI, color mode) and the pixel values of the red channel were plotted versus the known exposure and fit to a 4th degree polynomial to obtain the

calibration curve. Figure 4 shows the resultant calibration curve which allows a measure of the reflection density to provide a measure of exposure.

2.4 Verification

In order to check the validity of the GafChromic[®] film measurements, dose profiles were also measured with a 0.6 cc Farmer-type ionization chamber and compared to the profiles obtained with the film. Measurements of the dose were made by placing the Farmer chamber on the table as shown in Fig. 5 and the exposure rate was measured at positions along a line in increments of 1.0 cm in directions perpendicular and parallel to the anode-cathode axis. The 20 cm mode was used for the FPD and the Toshiba system was operated in cine mode (DA at 30 f/s). The profiles so obtained were compared with the profiles obtained with strips of Gafchromic film exposed under the same conditions. Since the 1.0 cm interval between the chamber measurements does not allow the curve to exactly follow sharp changes such as at the field edge, the chamber and film curves were matched for comparison by aligning the midpoint between the half maximums of each profile.

3. RESULTS AND DISCUSSIONS

3.1 Dose profiles in directions perpendicular and parallel to the anode-cathode axis

To determine the factors contributing to beam non-uniformity to areas of the skin inside and outside the collimated beam, dose profiles were obtained with the film in directions perpendicular and parallel to anode-cathode axis. Figure 6 shows the profile in a direction perpendicular to the anode-cathode axis obtained with full backscatter with the film and phantom on the table, similar to the patient exposure conditions. It is seen that the beam intensity drops by about 10% of the maximum at the beam edge due to backscatter falloff and that the extra-beam backscatter decreases slowly with distance from the field, being about 3% of the beam maximum at 6 cm from the edge and goes to nearly zero at 8 cm from edge. Figure 7 shows the beam profile obtained with the film in a direction parallel to the anode-cathode axis obtained with full backscatter with the film and phantom on the table, again similar to the patient exposure conditions. Due to the heel effect and backscatter, the beam is seen to decrease by about 40% on the anode side of the field.

3.2 Variation in dose profiles in a direction parallel to the anode-cathode axis

To evaluate the various sources of non-uniformity, the following measurements were made with and without the phantom in a direction parallel to the anode-cathode axis. In all cases the curves have been normalized to 100% at the center of the profile. Dose profiles were measured with various exposure conditions to determine their effect on field nonuniformity.

3.2.1 Variation with different filters at the same kvp—The variation in field uniformity with beam filtration was measured by using two different beam filters (1.8 mm Al and 0.3 mm Cu) at 125 kVp. The measurements were made with the phantom and without the phantom on the table to study the effect of backscatter. Figure 8 with the phantom shows that the backscatter outside the collimated beam for the copper filter is higher than for the aluminum filtered beam near the edge and almost the same further away from the beam edge. In both Figure 8 and Figure 9 the heel effect is more pronounced

with the aluminum filter than with the copper because of the lower energy in the spectrum with aluminum. Also the heel effect is slightly greater without backscatter in Figure 9 than with backscatter in Figure 8 due to the low frequency scatter contribution. As seen in Fig. 9 without the phantom backscatter, there is still a small “tail” outside the collimated beam which could be attributed to scatter from the table or the collimator or to off-focal radiation.

3.2.2 Variation with kVp for the same filter—The variation in heel effect and backscatter was measured using the 1.8 mm Al filter for three different kVps. As figure 10 and figure 11 shows, there is not much difference between the dose profiles for all three kVp's, whether with (Fig 10) or without (Fig. 11) the backscatter from the phantom. Figure 10 shows only a slight increase in the “tails” with increasing kVp due to increased extra-beam backscatter.

3.2.3 Difference between profiles for high kVp with Cu-filter and low kVp with Al-filter—Dose profiles were measured for the highest kVp with a 0.3 mm copper filter and for the lowest kVp with a 1.8 mm aluminum filter as available on the Toshiba Infinix C-Arm system. In both Figures 12 and 13, we can see that the harder x-ray beam (125 kVp, 0.3 mm Cu) had less variation due to the heel effect than the softer beam (60 kVp, 1.8 mm Al) and, in Figure 10, the harder beam with phantom is seen to have a greater percentage of backscatter outside the beam with a slower falloff. Both beams without backscatter in Figure 13 had about the same relative extra-beam scatter.

3.3 Variation in dose profiles in a direction perpendicular to the anode cathode axis

To determine the variation in backscatter at the skin independently of the heel effect, dose profiles were also measured in a direction perpendicular to the anode-cathode axis.

3.3.1 Profiles with and without the phantom—Figure 14 shows the dose profiles obtained in a direction perpendicular to the anode-cathode axis on the patient table with and without the phantom. The curves were normalized so that the value in the center of the profile without the phantom was 100. It is seen that with the phantom the dose is increased in the center of the beam by about 38% and drops from the center by about 10% at the beam edge. Backscatter outside the beam starts at over 20% of the primary beam and drops to about 3% of the primary beam at 6 cm from the edge.

3.3.2 Backscatter difference at different beam sizes—Figure 15 compares the profiles of backscatter from the phantom for two different field sizes. The curves were obtained as the difference between the profiles obtained with the phantom and without the phantom on the table, each normalized to the center of the beam without the phantom. These curves represent the distribution of scatter from the phantom for the 13 cm and 20 cm modes. Since the profiles in a direction perpendicular to the anode-cathode direction should be symmetric about the center, the average about the beam center is shown. There is little difference in the fractional increase due to backscatter at the center between both beams and the falloff of scatter outside the beams appears similar in shape.

3.3.3 Backscatter difference on the table and in air—The curves in figure 16 show the difference between the profiles obtained with the phantom and without the phantom when on the table and in air; each is normalized to the center of the beam without the phantom and the profiles were averaged about the beam center. These curves represent the distribution of scatter from the phantom for the two cases. It is seen that the table has very little measurable effect on the backscatter distribution as the curves are almost overlapping.

3.4 Verification with Ionization Chamber

To verify the accuracy of the film measurements, the 0.6 cc Farmer chamber was used to measure the dose profile for the same conditions as used with the film. Figures 17 and 18 show the results measured on the tabletop without backscatter at 80 kVp and 1.8 mm Al filter. Both curves were normalized by the same factor to obtain a value of 100 at the center of the field and superimposed for comparison. The results in Figure 17 and Figure 18 show the agreement between the dose profiles obtained with the scanned film and the ionization chamber. The agreement was very good with minor difference in the profiles because of the limited spatial resolution of the Farmer chamber and the 1.0 cm increment between chamber measurements, confirming the validity of the measured film profiles.

4. CONCLUSIONS

Non-uniformity of the x-ray beam due to the heel effect and patient backscatter are shown to be significant and would affect the actual dose distribution on the patient's skin during interventional fluoroscopic procedures. Inclusion of these factors in the skin-dose-distribution calculation with a dose tracking system can provide a more accurate determination of peak skin dose.

Acknowledgments

Support for this work was provided in part by NIH grants R43FD0158401, R44FD0158402, R01EB002873 and R01EB0084501 and by Toshiba Medical Systems Corporation.

References

1. Koenig TR, Wolff D, Mettler FA, Wagner LK. Skin injuries from fluoroscopically guided procedures: part 1, characteristics of radiation injury. *Am J Roentgenol*. 2001; 177(1):3. [PubMed: 11418388]
2. Wagner LK, Eifel PJ, Geise RA. Potential biological effects following high x-ray dose interventional procedures. *J Vasc Interv Radiol*. 1994; 5(1):71–84. [PubMed: 8136601]
3. Wagner LK, McNeese MD, Marx MV, Siegel E. Severe skin reactions from interventional fluoroscopy: Case report and review of the literature. *Radiology*. 1999; 213(3):773–776. [PubMed: 10580952]
4. Shope TB. Radiation-induced skin injuries from fluoroscopy. *Radiographics*. 1996; 16(5):1195–1199. [PubMed: 8888398]
5. Chugh K, Dinu P, Bednarek DR, Wobschall D, Rudin S, Hoffmann K, Peterson RR, Zeng M. A computer-graphic display for real-time operator feedback during interventional x-ray procedures. *Proc SPIE*. 2004; 5367:464–473.
6. Bednarek DR, Barbarits J, Rana VK, Nagaraja SP, Josan M, Rudin S. Verification of the performance accuracy of a real-time skin-dose tracking system for interventional fluoroscopic procedures. *Proc SPIE*. 2011; 7961:796127. [PubMed: 21731400]

7. Rana VK, Bednarek DR, Josan M, Rudin S. Comparison of skin-dose distributions calculated by a real-time dose tracking system with that measured by gafchromic film for a fluoroscopic c-arm unit. Med Phys. 2011; 38:3702.

Figure 1.
DTS display at the end of a cardiac procedure.

Figure 2.

Strip of GafChromic film following exposure showing the reflection density increase in the area passing through beam.

Figure 3.

Setup used for the measurement of dose profiles with backscatter on the patient table. The GafChromic film was placed under the solid-water phantom.

Figure 4.
Calibration curve determined for the GafChromic film.

Figure 5.

Setup for determination of the dose profile. The ionization chamber is placed on the table and moved in direction perpendicular to anode-cathode (left) and in the direction parallel to anode- cathode (right).

Figure 6.

Dose profile (normalized to 100 at the beam center) in a direction perpendicular to the anode-cathode axis with phantom on the table showing backscatter.

Figure 7. Dose profile (normalized to 100 at the beam center) in a direction parallel to the anode-cathode axis with phantom on the table showing nonuniformity due to heel effect and backscatter.

Figure 8.
Dose profile at 125 kVp for 1.8 mm Al and 0.3 mm Cu filter with phantom on table.

Figure 9.
Dose profile at 125 kVp for 1.8 mm Al and 0.3 mm Cu filter without phantom on table.

Figure 10.
Dose profile at 60 kVp, 80 kVp and 125 kVp for 1.8 mm Al filter with phantom on table.

Figure 11.

Dose profile at 60 kVp, 80 kVp and 125 kVp for 1.8 mm Al filter without phantom on table.

Figure 12.

Dose profile at 60 kVp for 1.8 mm Al filter and at 125 kVp for 0.3 mm Cu filter with phantom on table.

Figure 13.

Dose profile at 60 kVp for 1.8 mm Al filter and at 125 kVp for 0.3 mm Cu filter without phantom on table.

Figure 14.

Dose profiles for the 20 cm FPD mode obtained on the table with and without the phantom (normalized to 100 at the center of the beam without the phantom).

Figure 15.

Difference between the profiles obtained with the phantom and without the phantom on the patient table showing the variation of backscatter. (The vertical lines show the locations of the edges of the collimated beams.)

Figure 16.

Difference between the profiles obtained with the phantom and without the phantom showing the variation of backscatter for the phantom when on the table and in air. (The vertical line shows the location of the edges of the collimated beams.)

Figure 17.

Agreement between film and 0.6 cc Farmer chamber in a direction perpendicular to the anode-cathode axis.

Figure 18.

Agreement between film and 0.6 cc Farmer chamber in a direction parallel to the anode-cathode axis.