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Updates in the real-time Dose Tracking System (DTS) to improve the accuracy in calculating the radiation dose to the patients skin during fluoroscopic procedures

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Abstract

We have developed a dose-tracking system (DTS) to manage the risk of deterministic skin effects to the patient during fluoroscopic image-guided interventional cardiac procedures. The DTS calculates the radiation dose to the patient's skin in real-time by acquiring exposure parameters and imaging-system geometry from the digital bus on a Toshiba C-arm unit and displays the cumulative dose values as a color map on a 3D graphic of the patient for immediate feedback to the interventionalist. Several recent updates have been made to the software to improve its function and performance. Whereas the older system needed manual input of pulse rate for dose-rate calculation and used the CPU clock with its potential latency to monitor exposure duration, each x-ray pulse is now individually processed to determine the skin-dose increment and to automatically measure the pulse rate. We also added a correction for the table pad which was found to reduce the beam intensity to the patient for under-table projections by an additional 5–12% over that of the table alone at 80 kVp for the x-ray filters on the Toshiba system.

Furthermore, mismatch between the DTS graphic and the patient skin can result in inaccuracies in dose calculation because of inaccurate inverse-square-distance calculation. Therefore, a means for quantitative adjustment of the patient-graphic-model position and a parameterized patient-graphic library have been developed to allow the graphic to more closely match the patient. These changes provide more accurate estimation of the skin-dose which is critical for managing patient radiation risk.

Keywords

Interventional fluoroscopic procedures; dose tracking system; skin dose; fluoroscopy; dose mapping

1. INTRODUCTION

X-ray image guided minimally invasive interventional cardiac procedures are widely used. The duration of these procedures can be very long, leading to high levels of ionizing radiation being delivered to the patient and thus increased risk of deterministic skin effects.¹⁻⁵ In order to manage this risk, we have developed a Dose Tracking System (DTS) that calculates the radiation dose to the patient's skin in real-time by acquiring exposure parameters and imaging-system-geometry (beam orientation, patient table height and position, SID, etc.) from the digital bus on a Toshiba Infinix C-arm unit.⁶ The cumulative dose values are then displayed as a color map on a 3D graphic of the patient as seen in Fig. 1, for immediate feedback to the interventionalist. A number of recent upgrades have been made to the software to improve its performance.

The DTS acquires the exposure parameters and imaging-system-geometry from the digital bus on a Toshiba Infinix C-arm unit, and then calculates the dose delivered to the patients skin based on the acquired parameters. In the previous version of the DTS, the duration of the exposure was estimated by calculating the time difference between start and end of the exposure, which was determined by using the CPU clock intervals. In this study, we present the approach of processing individual x-ray pulses for skin-dose calculation so that the dependence of the exposure time on the CPU clock is eliminated and the pulse rate can be automatically calculated without the need for manual input.

To improve the accuracy of calculation, the effect of the table pad was also included in the determination of the exposure calibration data file. We are also developing a patient graphic library, which can be used to select a patient graphic depending upon patient height and weight before the start of the procedure. This helps to reduce the mismatch between the DTS patient graphic surface and the patient skin, thereby reducing error in calculated skin dose because of the inaccuracy in inverse-square-distance correction.

The DTS GUI was modified to make the GUI more user friendly and to display more information related to the procedure e.g. total fluoroscopy time, total reference point skin dose (RPSD), peak skin dose (PSD), and field of view peak skin dose (FOV PSD) are now displayed on the screen and may provide helpful feedback to the physician in managing risk of radiation injury to the patient. The DTS was further modified by adding the capability of quantitatively adjusting the patient graphic position on the table so as to better match the graphic position with the actual patient position.

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 percutaneous coronary intervention procedure.

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 cumulative dose and dose rate are calculated using the exposure parameters and an exposure calibration data file. The dose calculation 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 mR 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.

C++ and OpenGL were used to program the Dose Tracking System. A SYSTEC-electronics CAN-USB adapter⁷ was used to collect the exposure and the imaging-system-geometry parameters from the digital CAN bus on the Toshiba Infinix C-arm unit. For most events e.g. table motion, SID change, collimation change, x-ray exposure, the Toshiba Infinix unit generates a CAN message which can be read by the USB-CAN interface. Individual x-ray pulses can be identified by the DTS from the message ID of the CAN messages.

2.2 Processing of individual x-ray pulses for dose calculation

In the previous version of the DTS, the entrance skin exposure at the reference point (ESE_{REF}) is calculated using the pulse rate, PR, and the CPU exposure duration, t, by using the following equation:

$$ESE_{REF}(R) = X \left(\frac{R}{mAs} \right) \times \frac{PW(ms)}{1000} \times PR(s^{-1}) \times I(mA) \times t(s) \quad (1)$$

where X is the exposure per mAs at the reference point (15 cm from the gantry isocenter, towards the x-ray tube) including backscatter for the kVp and the filter used, PW is the pulse width in ms, and I is the x-ray tube current. The value of X is read from a calibration file which is generated by placing a calibrated ion chamber in the center of the x-ray beam on the tabletop under a 20 cm thick solid water phantom. Table height is adjusted so that the ion chamber lies at the reference point as in Fig. 2 and measurements of exposure per mAs with backscatter are made at different kVps and with the different filters available on the x-ray unit.

ESE_{REF} is used to calculate skin dose by using the following equation:

$$Absorbed\ Dose\ (Gy) = ESE_{REF}(R) \times F \times \left(\frac{focal\ spot\ to\ reference\ point\ distance}{focal\ spot\ to\ skin\ distance} \right)^2 \quad (2)$$

where F is the f-factor for soft tissue (0.0092 Gy/R), and the squared term in the equation gives the inverse-square-distance correction for each point on the patient graphic in the beam.

Because of the latency periods involved in the CPU while performing other functions, the time (t) determined for the exposure may not be accurate and an error may be introduced in the calculated skin-dose. Additionally, the x-ray pulse rate is not available on the digital bus and it needed to be manually input with the previous DTS software. In addition, the table pad was not included for generating the calibration files, and hence the effect of attenuation due to the table pad was not taken into consideration.

To make the calculation more accurate, the DTS was modified to read and identify the individual x-ray pulses, along with the mA, pulse width and kVp associated with each corresponding pulse. ESE_{REF} for a single pulse is then calculated by using the following equation:

$$ESE_{REF}(R) = X \left(\frac{R}{mA \cdot s} \right) \times \frac{PW(ms)}{1000} \times I(mA) \quad (3)$$

where X is the exposure per mAs from the calibration file at the kVp and the filter used, PW is the pulse width, and I is the current for that pulse. The calibration file for the upgraded version is generated using a setup similar to the one shown in Figure 2, but with the ion chamber placed on the table+pad, instead of the table alone. Skin dose is then calculated from the ESE_{REF} by using Eq. 2. In this way, the new approach calculates skin dose without the use of the CPU timer and the associated inaccuracies are eliminated from the dose calculations.

2.3 Automatic estimation of pulse rate

In the new method, pulse rate is not needed for the calculation of dose per pulse or cumulative dose. However, pulse rate is used to determine the dose rate and was calculated from the time difference between the timestamps of the consecutive x-ray pulse CAN messages provided by the Systec interface.

$$Pulse\ Rate_{calc} = \frac{1}{\Delta\tau(s)} \quad (4)$$

where τ = time difference between two consecutive x-ray pulses. Since, each x-ray system allows for only a limited set of discrete pulse rates to be used for exposure, the pulse rate calculated in Eq.4 is rounded to the nearest pulse rate available on the x-ray system. The instantaneous dose rate is then calculated by using the following equation:

$$Dose\ rate = Absorbed\ Dose\ per\ pulse\ (Gy) \times Pulse\ Rate_{calc}(s^{-1}) \quad (5)$$

The operational accuracy of the DTS system and its ability for tracking the x-ray beam intersection with a patient phantom and calculating skin dose in real-time was previously evaluated and shown to be excellent.^{8,9} To verify the accuracy of the new method for calculating the integrated dose and dose rate, a 15 cc calibrated ion chamber (Keithley Model 36050B) was placed in the center of the field above the pad on the tabletop and beneath the 20 cm solid water phantom to simulate the patient with a setup similar to that

shown in Fig. 2. Exposures were made for different kVps in both fluoroscopy and DA modes (modes normally used during cardiac interventional procedures) and with the various filters available on the Toshiba Infinix system, while the DTS calculated skin dose and dose rate on a graphic of a 2D flat object at the position of the chamber. Figure 3 shows the setup used for measuring skin dose and dose rate with the 20 cm solid water phantom.

2.4 Study of the patient table and table pad attenuation

In order to study the attenuation due to the table pad, exposure was measured without (I_{air}) and then with the table + table pad (I_{T+p}) as shown in Fig. 5. The beam was kept perpendicular to the table surface, and the measurements were repeated for different kVps. I_{air} and I_{T+p} were used to find $(\mu_T t_T + \mu_p t_p)$ by using the formula

$$I_{(T+p)} = I_{air} e^{-(\mu_T t_T + \mu_p t_p)} \quad (6)$$

where μ_T is the linear attenuation co-efficient of the table, t_T is the table thickness, μ_p is the linear attenuation co-efficient of the pad and t_p is the pad thickness.

To account for the variation in attenuation of the table and the pad due to the variation of the angle of transmission of the beam through the table and pad, the effective thickness of the table/pad can be calculated by using Eq.7.

$$t' = t [\tan^2(\alpha) + \tan^2(\beta) + 1]^{1/2} \quad (7)$$

where t is the actual table/pad thickness, α is the angle in the RAO/LAO direction and β is the angle in the CRA/CAU direction, as shown in Figure 4. It can be shown that with the table and the pad Eq. 8 holds

$$I_{(\alpha,\beta)} = I_{(0,0)} \times e^{-\mu_T t_T (\frac{t'_T}{t_T} - 1)} \times e^{-\mu_p t_p (\frac{t'_p}{t_p} - 1)} \quad (8)$$

where $I_{(\alpha,\beta)}$ = transmitted exposure through table+pad when α and/or β are non-zero, and $I_{(0,0)}$ = exposure when α and β are zero (i.e. beam direction perpendicular to the table surface). For DTS calculations, $I_{(0,0)}$ is same as the ESE_{REF} calculated by using Equation 3, and includes the scatter from table+pad, as well as backscatter from patient (simulated by using solid water). Using Eq.7 we can rewrite Eq.8 as

$$I_{(\alpha,\beta)} = I_{(0,0)} \times e^{-(\mu_T t_T + \mu_p t_p) ([\tan^2(\alpha) + \tan^2(\beta) + 1]^{1/2} - 1)} \quad (9)$$

A comparison of the effect of table and table+pad was performed by measuring transmission of x-rays through the table and table+pad. Exposure was measured at different kVps for the three different filters available on the Toshiba Infinix C-arm unit, with the ion chamber placed next to the flat panel detector (FPD) on the x-ray system, first with nothing, then with the table, and then with the table+pad, in the path of the beam as shown in Figure 5. The

gantry was angled in the cranial direction and measurements with the same setup were performed to determine the angular variation of transmission.

2.5 Development of patient graphic library

Accurate skin dose calculation depends on having a patient graphic model that closely matches the actual patient. Mismatch between the graphical surface and the patient surface will result in error in the dose calculation due to the difference in distance from the focal spot. For example, with a 70 cm distance from the source to the isocenter as on the Toshiba Infinix C-arm system and the entrance surface 15 cm from isocenter, a mismatch of the skin surface by 1 cm would result in an error of about 3.7% due to the inverse square as seen in Figure 6.

To simulate the patient, we developed 3D humanoid graphics with varying weights and heights, and morphed for body type by using the open source software application Makehuman.¹⁰ Various graphic models of ectomorphic, mesomorphic and endomorphic types can be generated by adjusting the muscle tone and other parameters (height, weight etc.) in the software. Each 3D model is then exported as a 3D interchange Collada (.dae) file. The model is then posed after importing the collada file into another open-source application Blender.¹¹ The model is then exported as a Wavefront (.OBJ) file which contains information on the vertices and the vertex normals of the polygonal facets which constitute the 3D humanoid surface. This information is read into the DTS as a mesh of triangles to form a 3D graphic representation of the patient. The DTS software is being designed such that the most appropriate body graphic can be automatically selected based on input of several basic patient dimensional metrics.

2.6 Updates in DTS GUI

A new GUI was developed for the DTS to provide needed information and to allow options to be selected at different window levels. Figure 1 shows the window of the DTS display that is seen during a procedure; this window displays the following information:

- a. Patient Information: Patient name and ID are displayed for patient identification purposes.
- b. Total Fluoroscopy Time: DTS keeps a track of the total time of fluoroscopic exposure made during the procedure.
- c. Total Reference Point Skin Dose (RPSD): During the procedure, the DTS calculates skin dose at the reference point (taken at 15 cm from the gantry isocenter towards the x-ray tube) for each pulse and integrates these values to calculate the total reference point skin dose, which is analogous to the reference point air kerma.
- d. Dose rate: DTS calculates the instantaneous peak skin dose rate in the FOV and displays it as a number as well as a colored bar, whose height is proportional to the dose rate value.
- e. Peak Skin Dose (PSD): Peak skin dose value gives the aximum value of skin dose at any point on the patient.

- f. Field of View Peak Skin Dose (FOV PSD): FOV PSD gives the peak skin dose value in the current location of the x-ray beam at that instant. The same value is also displayed as a color bar, and is updated whenever an exposure is made or the location of the x-ray beam is moved so that it would intersect a different region of the patient skin.

The DTS updates the values displayed on the screen in real time during the procedure for immediate feedback to the physician (Figure 7).

Separate windows include the capability of the inputting patient information such as patient name, D.O.B, age, sex, weight and height, and study information such as physicians name and type of procedure (See Figure 8). This information is recorded in a PDF report at the end of the procedure and can be helpful for reviewing the patient case later.

Improved capability for changing the patient graphic position on the patient table was added to the DTS. Figure 9 shows a screenshot of the DTS GUI that is used for changing the patient graphic position on the patient table. In the old version of the DTS, the user could change the position of the patient graphic on the table, but no quantitative information of the distance was available to the user. In the new version, the position of the graphic can be changed along the three orthogonal directions (CRA-CAU, right-left and vertical position relative to the table) either by moving the slider bars or by entering the distance values in centimeters relative to the default position of the graphic on the table (see Figure 9). The zero default positions are with the top of the head of the graphic aligned with the gantry edge of the table (CRA-CAU), with the patients center aligned with the table center in the left-right direction, and with the graphics back on the table top (pad included). Table pad thickness could vary in different facilities, so the DTS includes pad thickness as a setup parameter that can be entered during DTS installation, and can also be modified later if the table pad is changed.

2.7 Generation of report at the end of the procedure

The DTS automatically saves a report at the end of the procedure. The report is saved in the PDF format and includes information such as patient name, ID, D.O.B, total fluoroscopy time, total DA time, PSD value and a screen shot of the patient graphic showing the skin dose distribution in color from the perspective of the peak value. Additional information has been added such as physicians name, location where the study was performed, procedure notes (if any), and type of procedure (e.g. PCI, diagnostic, grafts etc). Other selected procedure information can be included such as the range of CRA-CAU and LAO-RAO angles used during the procedure which has been included on the current report for our reference. Figure 10 shows a sample report from a PCI procedure.

3. RESULTS AND DISCUSSION

The graph in figure 11 shows a comparison of the dose rate values calculated by using the DTS and as measured by using a 15 cc ion chamber as shown in Figure 3, while Figure 12 shows a comparison of the integrated dose values for the same setup. The difference between calculated and measured values was found to be less than 0.5% for the dose rate as

well as for the integrated dose values. Figure 13 (a) shows the variation in $(\mu_T t_T + \mu_P t_P)$ as a function of the kVp for the three different filters available on the Toshiba Infinix C-arm unit, while Figure 13(b) shows the ratio of x-ray beam intensity transmitted through table+pad and intensity measured in air, at different kVps for the three filters. As seen in the graph in Figure 13(b), the beam is attenuated by about 20–40%, depending on the spectrum of the beam. Table 1 shows a comparison of the transmission through the table alone and table +pad at 80 kVp for the three filters. From Table 1 it is clear that the pad has a measurable effect on the beam intensity, and hence a correction factor should be included to account for its attenuation along with that of the table. Figure 14 shows the transmission through table +pad as function of different gantry (CRA) angles for the three filters measured by using 80 kVp beam. Black trendlines represent the values calculated by using Eq. 8. The difference between the measured and calculated values was found to be less 1%.

A series of male and female body graphic models have been developed which vary in weight and height. Matching pairs have been constructed with arms at the side and over the head to simulate the usual placement in cardiac procedures, as shown in figures 15, 16, and 17.

Currently the DTS program has sets of 15 male and 15 female graphic models as shown in Figures 18 and 19. The graphic models cover a range of weights and heights that can be selected from, at the beginning of a procedure and can be optionally drawn with arms raised above the head.

4. CONCLUSIONS

We have developed a new version of the DTS in which individual x-ray pulses are processed to calculate skin dose to the patient without having to measure exposure duration, thereby eliminating inaccuracies introduced because of the latency periods in the CPU timers. The new version is also capable of estimating pulse rate automatically. Error in skin dose and dose rate calculation was found to be less than 0.5% when using the new approach. Both the patient table and pad were found to have measurable effect on the beam intensity and both are included in the dose calculation to improve the accuracy in the calculation. A library of categorized body shapes should allow close matching of the graphic to the patient shape thereby providing more accurate determination of skin dose with the DTS. If the graphic can match the position of the patients skin surface within 1 cm, the error in skin dose calculation due to inverse-square correction is expected to be below 5% for most C-Arm systems. Further the ability to quantitatively adjust the position of the graphic should provide more precise matching of the graphic to the patient position and more accurate calculation. Use of the individual pulse processing approach to calculate skin dose to the patient during fluoroscopic interventional procedures, the inclusion of a correction for attenuation due to the table pad and a better matching of the patient graphic will provide a more accurate calculation of the skin dose.

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Figure 1.

DTS display at the end of a Percutaneous Coronary Intervention procedure performed on a 59 yr old male (Height: 5'6", Weight: 150 lbs).

Figure 2.

Schematic showing the setup used for generating calibration files for use in the DTS.

Exposure is measured at different kVps and by using different filters available on the x-ray machine, with a calibrated ion chamber placed on the patient table and beneath 20 cm solid water (used to simulate patient backscatter).

Figure 3.

Setup used for comparing the dose and dose rate values calculated by the DTS to that measured by using a 15 c.c. ion chamber. The ion chamber was placed beneath 20 cm of solid water to simulate the patient. Table height was adjusted so that the ion chamber is at 15 cm from the isocenter towards the x-ray tube (a typical position for the patient entrance skin surface during cardiac procedure).

Figure 4.

Schematic showing the change of effective table and pad thickness as seen by various elements on the patient graphic depending on the angulation of the beam through the patient table and pad.

Figure 5.

Schematic of the setups used for comparing the attenuation effect of table and table+pad. Ion chamber was placed next to the FPD, first in air to measure the primary beam intensity (a), then with the table in the beam path (b), and then with the table+pad in the beam path (c).

Figure 6.

Graph showing the error in dose calculation as a function of the mismatch between the patient graphic and actual patient surface along the beam direction, with the isocenter at 70 cm from source and with the skin surface 15 cm tube side of the isocenter. Negative displacement indicates graphic mismatch towards the tube, while positive displacement indicates graphic mismatch away from the tube.

Figure 7.

DTS data display during a procedure. The DTS display was modified to include patient information, total fluoroscopy time during the procedure, total reference point skin dose (RPSD), instantaneous skin dose rate, peak skin dose (PSD), field of view peak skin dose (FOV PSD) etc. Dose rate and FOV PSD are also displayed as color bars for providing a visual feedback to the physician.

The image shows two side-by-side windows from a software application. The left window is titled "Patient Information" and contains the following fields: "Date" (12/24/2012), "Patient ID", "Last Name", "First Name", "D.O.B (mm/dd/yyyy)", "Gender" (radio buttons for Male and Female, with Male selected), "Weight" (radio buttons for lbs and kgs, with lbs selected), and "Height" (radio buttons for ft and in, with ft selected, and a secondary option for cms). There are "Clear" and "OK" buttons at the bottom. The right window is titled "Study Info" and contains: "Physician", "Technologist", "Room", "Procedure" (checkboxes for Diagnostic, PCI, Grafts, and (R)Heart, with Other as a text input), "Procedure Notes" (a large text area), and "Cancel" and "OK" buttons at the bottom.

Figure 8.

A screen shot of the DTS windows for inputting patient information such as patient name, D.O.B, sex, weight, height etc, and study information such as physicians name, type of procedure etc.

Figure 9.

Capability of quantitatively positioning the patient graphic in the DTS was added. Graphic position on the patient table can be changed by moving the slider bars or by manually entering the position of the graphic in centimeters.

Figure 10.

A sample DTS dose report generated at the end of the procedure.

Figure 11.

Graph showing the ratio of dose rates as calculated by the DTS to that measured by a 15 cc ion chamber with the setup shown in Figure 4.

Figure 12.

Graph showing the ratio of skin dose as calculated by the DTS to that measured by a 15 cc ion chamber with the setup shown in Figure 4.

Figure 13.

(a) $(\mu_T t_T + \mu_P t_P)$ shown as function of kVp for three different filters on the Toshiba Infinix C-arm unit. (b) the ratio of beam intensity transmitted through the table+pad to the intensity measured in air, as a function of kVp for the three filters on the Toshiba Infinix C-arm unit.

Figure 14.

The beam intensity measured after transmission through the table+pad as function of CRA angles for 3 beam filters. The black trend-lines represent the values calculated by using Eq. 9.

Figure 15.

Examples of 35 yr. old male patient 3D graphic models: (a) 66" tall male patient; (b) the same height but 25% less weight than in (a); (c) same graphic as in (a) but with arms raised for lateral cardiac projection; (d) a shorter 60" male patient; and (e) posterior view of the patient in (a) as seen for under-table tube exposure.

Figure 16.

Examples of female-patient 3D graphic models: (a) a 40 yr. old and 63" tall female patient; (b) same height but 25% less weight than in (a); (c) same graphic as in (a) but with arms raised for lateral cardiac projection; (d) a younger (25 yr. old) and shorter (56" tall) female patient; and (e) posterior view of the patient in (a).

Figure 17.

Examples of pediatric 3D graphic models: (a) 42" tall child patient graphic. (b) a patient graphic with same height as in (a) but with 33% greater weight, and (c) a graphic model with 66% greater weight than in (a).

Figure 18.

Set of 15 male graphics included in the DTS to represent a range of patients with different heights and weights. Models were generated by using different height and weight parameters in the Makehuman software.

Figure 19.

Set of 15 female graphics included in the DTS to represent a range of patients with different heights and weights. Models were generated by using different height and weight parameters in the Makehuman software.

Table 1

Comparison of the transmission through the table vs the table+pad, for three different filters at 80 kVp.

	Filter 1 (0.2 mm Cu)	Filter 2 (0.3 mm Cu)	Filter 3 (1.8 mm Al)
Table	82.6%	82.8%	77.8%
Table + Pad	76.7%	77.3%	69.3%