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A Real-Time Skin Dose Tracking System for Biplane Neuro-Interventional Procedures

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Abstract

A biplane dose-tracking system (Biplane-DTS) that provides a real-time display of the skin-dose distribution on a 3D-patient graphic during neuro-interventional fluoroscopic procedures was developed. Biplane-DTS calculates patient skin dose using geometry and exposure information for the two gantries of the imaging system acquired from the digital system bus. The dose is calculated for individual points on the patient graphic surface for each exposure pulse and cumulative dose for both x-ray tubes is displayed as color maps on a split screen showing frontal and lateral projections of a 3D-humanoid graphic. Overall peak skin dose (PSD), FOV-PSD and current dose rates for the two gantries are also displayed. Biplane-DTS uses calibration files of mR/mAs for the frontal and lateral tubes measured with and without the table in the beam at the entrance surface of a 20 cm thick PMMA phantom placed 15 cm tube-side of the isocenter. For neuro-imaging, conversion factors are applied as a function of entrance field area to scale the calculated dose to that measured with a Phantom Laboratory head phantom which contains a human skull to account for differences in backscatter between PMMA and the human head. The software incorporates inverse-square correction to each point on the skin and corrects for angulation of the beam through the table. Dose calculated by Biplane DTS and values measured by a 6-cc ionization chamber placed on the head phantom at multiple points agree within a range of -3% to +7% with a standard deviation for all points of less than 3%.

Keywords

Interventional fluoroscopic procedures; dose tracking system; skin dose; fluoroscopy exposure; dose mapping; biplane imaging system; neuro-interventions

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1. INTRODUCTION

In the recent past, use of x-ray image-guided minimally invasive interventional procedures for treating neurovascular anomalies has increased. The duration of these procedures is often very long, resulting in a large amount of ionizing radiation being delivered to the patient and thus increased risk of deterministic skin effects.¹ To help control patient dose during these procedures, we have developed a dose tracking system (DTS) that can be used to calculate skin dose in real-time for feedback to the physician.^{2, 3}

Since neuro-interventional procedures are often performed using a biplane imaging system, the DTS must be able to monitor dose from each x-ray tube. The Biplane-DTS was designed to acquire geometry and exposure parameters from the two gantries of the imaging system and from the patient table in real time from a digital bus on the imaging system. The DTS software reads and is able to differentiate the acquired geometry parameters from the bus (i.e. if the data packet is associated with one of the gantries or the patient table) and updates the corresponding modeled component in the Biplane-DTS software. Similarly, the gantry of origin for exposure parameters is identified, and the dose to the patient's skin is calculated within the corresponding gantry's x-ray beam. Skin dose is calculated by using calibration data acquired specifically for the neuro-interventional procedures and the cumulative value at each point on the surface is displayed in real-time as a color-coded 3D map on a human graphic used to simulate the patient's skin surface. Figure 1 shows the layout of the Biplane-DTS display developed for biplane imaging systems.

2. MATERIAL AND METHODS

A biplane imaging acquires obtains x-ray images with two imaging gantries from two different projections. The biplane images are shown in real time and allow the physician to conceptualize a 3D perspective of the patient vasculature and thus help guide catheters and place devices such as coils in aneurysms. In addition to fluoroscopy, neuro-interventional procedures commonly use the higher dose per frame digital angiography (DA) and digital subtraction angiography (DSA) modes. Depending on the number and condition of the malformations and accessibility of the site, the procedure may take a very long time. Since a biplane imaging system uses two x-ray tubes simultaneously to make exposures, radiation dose to the patient becomes even higher.

We have earlier demonstrated a dose tracking system that is compatible with a single plane Toshiba Infinix C-arm unit, and that was designed to track patient skin dose principally for cardiac interventional fluoroscopic procedures. The scattering properties of a human head is expected to be different than that of the torso region because of differences in surface shape and size and the underlying bone in the head. Thus, cardiac DTS was modified to be able to track patient skin dose to the head during neuro-interventional procedures, which very often use biplane imaging, and to make this dose information available to the physician for immediate feedback so that the risk of the radiation-induced skin injuries can be reduced.

MS Visual C++ was used to develop a graphical user interface (GUI) for the Biplane-DTS (shown in figure 1). C++, CUDA and OpenGL were used to develop different classes for

data handling and skin dose calculations. The Biplane-DTS has been programmed such that the patient graphic data resides on the GPU memory and all corresponding calculations are done on the GPU using its paralleling processing power and thus making the Biplane-DTS fast enough for real-time dose calculations.

2.1 Data Acquisition

Whenever there is a geometry change (e.g. patient table position is changed, gantry is rotated, beam is collimated, or SID is changed) or if the exposure status changes (e.g. if exposure is started or stopped, if filter is changed, or imaging mode is changed) this information is relayed in the form of digital data packets called 'CAN messages' over a digital CAN (Controller Area Network) bus on the Toshiba Infinix system. A CAN message is relayed for each type of geometric or exposure change.

The Biplane-DTS computer is connected to the x-ray system computer through a SYSTEC-USB CAN module (USB-CANmodul1, SYS TEC Electronics, Heinsdorfergrund, Germany) which is used to read the CAN messages being relayed on the digital CAN bus.⁴ The CAN module is connected in parallel with the digital bus carrying data between the x-ray system and the x-ray system computer. This allows the module to 'listen' to CAN data being relayed on the CAN bus without interrupting the operation of the x-ray system as shown in Figure 2.

The DTS reads the CAN messages from the CAN module in a 'FIFO' fashion and processes each message one at a time. During processing the DTS identifies the message by using its unique ID, and assigns the data to the corresponding simulated part in the DTS e.g. if the first message on the CAN bus originated from the frontal gantry, then it is used to update the corresponding variable of the simulated frontal gantry in the DTS and so on (see figure 3).

Whenever the system geometry changes (e.g. if a gantry is moved, or the patient table is moved, or operator adjusts the patient graphic position on the patient table), the Biplane-DTS determines the areas of the patient graphic surface (defined by a set of 3D vertices) that are within the x-ray beams. When an exposure is made, the Biplane-DTS identifies the gantry and exposure parameters such as tube current (I), kVp and pulse width (PW) used for making the exposure. The Biplane-DTS then calculates the skin dose for individual graphics vertices within the beam as explained below.

2.2 Dose Calculation

The Biplane-DTS uses the CAN information for each x-ray pulse to determine the appropriate calibration factors ($X_{kVp,proj}$) from the calibration files that contain the ESE per mAs values (including backscatter) measured at the surface of a 20 cm PMMA phantom as a function of the kVp for the corresponding tube, added filter, imaging mode (fluoroscopy or DA) used, and the projection (*proj*) for the vertex rays 'passing through' or 'not passing through' the patient table+pad (*proj* = 1 if passing through the table+pad; *proj* = 2 if not passing through the table+pad).

Calibration files for $X_{kVp,proj}$ are generated by measuring the ESE per mAs as a function of kVp and beam filter at the surface of a 20 cm thick PMMA phantom, by placing the

phantom on table+pad top for frontal projections (see figure 4a) and in air for lateral projections (see figure 4b). A PTW SFD 6 c.c. calibrated ionization chamber (Type 34069, PTW, Freiburg, Germany) was used for measuring exposures.⁵

Reference point entrance skin exposure (including backscatter from the patient), $ESE_{(REF, proj)}$, values are calculated by using the corresponding $X_{kVp, proj}$ value in the following equation:

$$ESE_{(REF, proj)}(mR) = X_{(kVp, proj)} \left(\frac{mR}{mAs} \right) \times \frac{PW(ms)}{1000} \times I(mA) \quad (1)$$

where PW is the pulse width and I is the tube current. Backscatter from the patient head is expected to be different from that of the 20 cm PMMA phantom because of the difference in their composition, shapes and sizes. Backscatter from the head is also expected to vary with the field area of the skin entrance surface. Thus we apply a correction for variation in ESE as a function of entrance field area, using by applying area correction factors measured for the SK-150 head phantom.⁶ We used an SK-150 head phantom because it consists of an actual human skull and thus its scattering properties are expected to be close to that of an actual patient head. Correction for the SK-150 head is applied by using the entrance field area $area_{ent}$ as follows:

$$ESE_{(REF, proj, area)}(mR) = ESE_{(Ref, proj)}(mR) \times (a_{proj} \times \ln(area_{ent}) + b_{proj}) \quad (2)$$

where $ESE_{(REF, proj, area)}$ is the area corrected $ESE_{(REF, proj)}$, $area_{ent}$ is the x-ray field area at the entrance skin surface, and (a_{proj}, b_{proj}) are the area correction factor fit parameters for the SK-150 head, read from the area correction file for the corresponding x-ray tube and the beam filter. Correction files were generated by measuring entrance exposure at the SK-150 head phantom, as a function of entrance area and beam filter used. Figure 4c shows the schematic of the setup used for SK-150 head measurements. Different data sets were acquired for the frontal and lateral tubes, in both fluoroscopy and angiography modes.

The next step in dose calculation is to calculate the dose for individual graphic vertices by applying an inverse square distance correction and table+pad attenuation correction for non-perpendicular rays. For the vertices which have been marked 'within the beam' by the Biplane-DTS earlier during geometry updates, absorbed dose to be added $Dose_v$ is calculated by using Eq.3, as follows:

$$\Delta Dose_v(mGy) = ESE_{(REF, proj, area)}(mR) \times f \times \left(\frac{d_{ref}}{d_v} \right)^2 \times F_{atten} \quad (3)$$

where f = f-factor for soft tissue, d_{ref} is the focal spot to reference point distance, d_v is the focal spot to patient-graphic vertex distance, and F_{atten} is the attenuation correction factor for rays which are non-perpendicular to the table given by

$F_{atten} = e^{-(\mu_{TT} + \mu_{PT}) \cdot (\sec(\theta) - 1)}$ for those vertices with the corresponding vertex-ray passing through the patient table+pad (i.e. $proj = 1$), where θ is the angle between the table normal and the ray directed from the focal spot to the vertex, and $(\mu_{TT} + \mu_{PT})$ is a kVp and added

filter dependent attenuation factor at perpendicular incidence of the beam read from a pre-generated file; or

$F_{atten} = 1$ for those vertices with the corresponding vertex-ray not passing through the patient table (i.e. $proj = 2$).

$Dose_v$ is added to the previous cumulative value of the vertex dose $Dose_v$, to get the new dose value for the corresponding vertex, i.e.

$$Dose_v (mGy) = Dose_v (mGy) + \Delta Dose_v (mGy) \quad (4)$$

The calculated dose is then used to assign an 'RGB' color to the patient graphic vertex and the set of vertices are rendered on the screen as the color-coded 3D human graphic, formed by a set of 3D triangular elements where each triangle is defined by a set of 3 nearest-neighbor vertices. At the same time, the Biplane-DTS also updates the values of PSD, FOV-PSD, dose rates and fluoroscopy and angiography times on the monitor.

The accuracy of the Biplane-DTS was tested by placing the SK-150 head phantom on the table and making exposures with a PTW 6 cc ionization chamber in the beam center with both tubes. Gantry positions, beam collimation and table height were changed while making exposures and the chamber was repositioned accordingly. Values measured by the ionization chamber were compared to those calculated by the Biplane-DTS.

3. RESULTS AND DISCUSSION

The graphs in figure 5 shows the ESE measured at the entrance surface of the 20 cm PMMA phantom for calibration of the Biplane-DTS using the frontal tube in fluoroscopy and DA modes and the set up for frontal projections (as shown in figure 4a) with a field area of 239 cm^2 at the phantom entrance surface. A field area of 239 cm^2 corresponds to the 10 inch mode of the FPD with an SID of 90 cm and represents the beam size used most commonly for the interventional procedures in the clinic. It is observed that the ESE per mAs is higher in the DA mode than the fluoroscopic mode. This difference is due to the different x-ray pulse shapes produced by the x-ray generator in the two modes.

The graph in figure 6 shows the relative ESE measured at the entrance surface of the SK-150 head phantom as a function of entrance field area and beam filter of the Biplane-DTS using the frontal tube in fluoroscopy mode and set up used for frontal projections (as shown in figure 4c). These values were measured with the table (Figure 6a) and without the table (Figure 6b); and are given relative to the PMMA ESE measured for a 239 cm^2 field size and are the correction factors applied for the head phantom and field size. Figure 7 shows a color-coded mapping of the dose distribution for a simulated biplane neuro-procedure.

To determine the accuracy of the Biplane-DTS dose estimation, the SK150 head phantom was placed on the patient table with the "interventional volume of interest" at the gantry isocenter and the entrance dose was measured with an ionization chamber placed on the phantom in the center of the beam; measurements were made with the ionization chamber

moved to random positions on the phantom and the angulation of the gantry and the patient table repositioned so that the chamber was again in the beam center. LAO/RAO angles between 0-100° for the frontal tube and 0-40° for the lateral tube, and CRA/CAU angles in the range of 0-30° were used for the two gantries for making exposures. Figure 8 shows the ratio of the skin dose calculated by the Biplane-DTS to that measured with the ionization chamber for 18 positions on the phantom. The 18 ratios had a mean value of 1.014 and varied between -3 to 7%, with a standard deviation of <3%

4. CONCLUSIONS

We have developed a dose tracking system (Biplane-DTS) that can acquire and identify geometry/exposure parameters from a Toshiba Infinix Biplane™ system during neuro-interventional fluoroscopic procedures and use this data to calculate patient skin dose with high accuracy. The calculated dose can be displayed in real-time as 3D color maps on human graphics showing the frontal and lateral projections of a biplane imaging system for immediate feedback to the physician.

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Figure 1.

Screenshot of the Biplane-DTS showing various parts of the display. The patient graphic is displayed in a split-screen, showing the position of the frontal and lateral x-ray beams in the left and right sub-windows, respectively. Other useful information related to the procedure e.g. total angiography and fluoroscopy exposure times used on the two gantries, overall peak skin dose (PSD), PSD in the current field of view of each x-ray beam (FOV PSD) and current skin dose rate for each tube is also displayed in the panel on right.

Figure 2.

Schematic showing the flow of CAN data (red line paths) between (a) the x-ray system, (b) x-ray system computer, (c) SYSTEC-USB CAN module and (d) the Biplane-DTS computer.

Figure 3.

Schematic showing the processing of the incoming CAN data by the Biplane DTS. The CAN messages are processed in the same sequence as they were received by the CAN module, and the processed information is immediately applied to the corresponding part of the dose tracking system.

Figure 4.

Schematics showing setup used for acquiring calibration data with 20 cm PMMA, as a function of kVp and beam filter used for exposure (a) with the phantom placed on table+pad (for frontal projections), (b) with the phantom exposed laterally (without table+pad in the beam path) for lateral projections, and (c) Setup used for generating correction files for variation in SK-150 phantom ESE with entrance field size, with frontal projection. A setup similar to (b) is used for generating correction files for lateral projections of SK-150, but without changing the phantom orientation from (c).

Figure 5.

The ESE measured at the surface of a 20 cm PMMA phantom placed on the table+pad for the frontal tube (a) in fluoroscopy mode and (b) in digital angiography mode with a 239 cm^2 field, as a function of kVp and added beam filter used. The solid curves are 2nd degree polynomial fits to the data.

Figure 6.

Normalized ESE values measured in fluoroscopy mode for the SK-150 head phantom as a function of field area and using frontal tube (a) with the table+pad in the beam path, and (b) in air. SK-150 ESE values are normalized to the calibration data acquired with PMMA for the corresponding filter and a field size of 239 cm^2 . Black curves show log fits ($a \times \ln(\text{area}) + b$, where a, b are the fit parameters) to the data. Values of the fit parameters (a, b) are shown in the parentheses next to the curves.

Figure 7.

Screen shot of the Biplane-DTS display at the end of a simulated neuro-interventional procedure, performed by placing the SK-150 head phantom on the patient table. The cumulative skin dose from both tubes is given on each graphic and shown from two projection views.

Figure 8.

Ratio of the skin dose calculated by the Biplane-DTS to the dose measured by placing an ionization chamber on the SK-150 head phantom surface. For each position number, the ionization chamber was in the center of the beam with the gantry at different angulations for the frontal and lateral tubes. (Mean = 1.014, Std. dev = 0.023)