A tracking system to calculate patient skin dose in real-time during neurointerventional procedures using a biplane x-ray imaging system

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Purpose: Neurovascular interventional procedures using biplane fluoroscopic imaging systems can lead to increased risk of radiation-induced skin injuries. The authors developed a biplane dose tracking system (Biplane-DTS) to calculate the cumulative skin dose distribution from the frontal and lateral x-ray tubes and display it in real-time as a color-coded map on a 3D graphic of the patient for immediate feedback to the physician. The agreement of the calculated values with the dose measured on phantoms was evaluated.

Methods: The Biplane-DTS consists of multiple components including 3D graphic models of the imaging system and patient, an interactive graphical user interface, a data acquisition module to collect geometry and exposure parameters, the computer graphics processing unit, and functions for determining which parts of the patient graphic skin surface are within the beam and for calculating dose. The dose is calculated to individual points on the patient graphic using premeasured calibration files of entrance skin dose per mAs including backscatter; corrections are applied for field area, distance from the focal spot and patient table and pad attenuation when appropriate. The agreement of the calculated patient skin dose and its spatial distribution with measured values was evaluated in 2D and 3D for simulated procedure conditions using a PMMA block phantom and an SK-150 head phantom, respectively. Dose values calculated by the Biplane-DTS were compared to the measurements made on the phantom surface with radiochromic film and a calibrated ionization chamber, which was also used to calibrate the DTS. The agreement with measurements was specifically evaluated with variation in kVp, gantry angle, and field size.

Results: The dose tracking system that was developed is able to acquire data from the two x-ray gantries on a biplane imaging system and calculate the skin dose for each exposure pulse to those vertices of a patient graphic that are determined to be in the beam. The calculations are done in real-time with a typical graphic update time of 30 ms and an average vertex separation of 3 mm. With appropriate corrections applied, the Biplane-DTS was able to determine the entrance dose within 6% and the spatial distribution of the dose within 4% compared to the measurements with the ionization chamber and film for the SK150 head phantom. The cumulative dose for overlapping fields from both gantries showed similar agreement.

Conclusions: The Biplane-DTS can provide a good estimate of the peak skin dose and cumulative skin dose distribution during biplane neurointerventional procedures. Real-time display of this information should help the physician manage patient dose to reduce the risk of radiation-induced skin injuries. © 2016 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4960368>]

Key words: interventional fluoroscopic procedures, dose tracking system, skin dose mapping, biplane imaging system, neurointerventions

1. INTRODUCTION

Biplane neurointerventional fluoroscopic systems are used mainly to treat vascular conditions involving the central nervous system such as aneurysms, arteriovenous malformations, and stroke. A biplane system is equipped with two completely separate imaging chains that simultaneously acquire lateral and frontal images and show these images in real-time on

a monitor to the physician. Biplane images provide a 3D perspective of the patient vasculature and thus help to provide a “road map” of the blood vessels.

During an interventional fluoroscopic procedure, the patient may be exposed to large amounts of radiation from fluoroscopy and the higher dose per frame digital angiography (DA) and digital subtraction angiography (DSA) modes. The amount of radiation to which the patient is exposed depends

on many factors such as the length of the procedure, the patient size, and the imaging mode being used. Procedures such as embolization and coil or stent placement may take a very long time, depending on the number and condition of the malformations and accessibility of the site. During such procedures, the skin gets the highest amount of soft-tissue dose and is thus at the highest risk for radiation-induced injuries.¹⁻⁴ The risk of radiation-induced skin injuries can be reduced by lowering the total amount of dose delivered to the patient during the interventional procedure or by distributing the dose over the skin surface by moving the beam entry location.

The risk of deterministic radiation injury to the skin can be assessed in terms of the peak skin dose (PSD), which is the highest dose occurring at any point on the skin surface. Many methods have been used to estimate the dose to the patient's skin during a procedure. These include the metrics of reference point air kerma (RPAK) or cumulative air kerma,⁵⁻⁷ fluoroscopy time, dose area product (DAP) or kerma area product (KAP),⁷ as well as direct measurement with radiochromic film or thermoluminescent dosimeters (TLDs), and calculation from the data in the DICOM radiation dose structured report (RDSR).⁸ These methods either are inaccurate in calculating the skin dose or cannot be applied in real-time or both. To allow the physician to manage radiation dose during the procedure so that the risk of the radiation-induced skin injuries can be reduced, a system is needed which can monitor the patient skin dose distribution in real-time and make accurate skin dose information available for immediate feedback.

Here we report on a biplane dose tracking system (Biplane-DTS) software program that we developed for the Toshiba Infinix™-i Bi-plane system.⁹ The Biplane-DTS can monitor and display the patient skin-dose distribution in real-time during neurointerventional procedures and thus will help in preventing radiation-induced skin injury to the patient. Figure 1 shows the layout of the Biplane-DTS display developed for use with biplane imaging systems so that both lateral and frontal beams can be viewed simultaneously. We have earlier demonstrated a dose tracking system that is compatible

with a single plane C-arm unit, and that was designed to track patient skin dose principally for cardiac interventional fluoroscopic procedures.¹⁰ That DTS was modified to be able to track and display in real-time the patient skin dose to the head during biplane neurointerventional procedures.

2. METHODS

2.A. System design

MS Visual c++ was used to develop a graphical user interface (GUI) for the Biplane-DTS. 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 reside on the GPU memory and all corresponding calculations are done on the GPU using its parallel processing power and thus making the Biplane-DTS fast enough for real-time dose calculations.¹¹

2.B. Data acquisition

All information about the exposure conditions and the geometry of the imaging system is relayed to the DTS software through a digital controller area network (CAN) bus on the C-arm system as seen in Fig. 2.⁹ Whenever there is a geometry change (e.g., patient table position is changed, gantry is rotated, beam is collimated, SID is changed) or if the exposure status changes (e.g., exposure is started or stopped, filter is changed, imaging mode is changed), this information is relayed in the form of digital data packets.

For each geometry change, 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. The Biplane-DTS also determines the patient graphic vertices for which the corresponding vertex ray (ray directed from the x-ray tube focal spot to the vertex) passes through the patient table, so that

FIG. 1. Screenshot of the Biplane-DTS display. The patient graphic is displayed in a split-screen, showing the projection of the frontal and lateral x-ray beams in the left and right subwindows, respectively. Other useful information related to the procedure such as total angiography and fluoroscopy exposure times used on the two gantries, overall 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 the right.

FIG. 2. Schematic showing the processing of the incoming CAN data by the Biplane-DTS. The CAN messages are processed in the same sequence as they are received by the CAN module, and the processed information is immediately applied to the corresponding part of the dose tracking system.

appropriate table attenuation correction can be applied during dose calculation. When an exposure is made, the Biplane-DTS identifies the gantry and exposure parameters and calculates the skin dose for individual vertices of the graphic within the beam as explained later.

2.C. Biplane-DTS calibration

In order to accurately calculate patient skin dose, it is necessary that the Biplane-DTS simulates the geometry of the biplane imaging system and the exposure properties of the x-ray beams. Exposure properties include the tube x-ray output, variation in the x-ray beam intensity with distance from the source to the skin surface, variation in beam intensity as a function of the field size, backscatter from the patient, and effects of different objects such as added filters and the patient table in the beam path. Various configuration and calibration files are included in the Biplane-DTS. Gantry-specific configuration files include information such as focal spot to isocenter distance, focal spot to collimator distance, gantry c-arm radii, a list of 3D vertices that define the patient table, and table pad thickness. Calibration files contain the entrance skin dose (ESD) per mAs values (including backscatter and the air kerma to soft tissue conversion factor, and where mAs is the product of tube current times pulse width times the number of pulses per exposure) measured at the surface of a phantom that can simulate the tissue properties of a patient, as a function of the kVp for the corresponding tube, added filter, and imaging mode (fluoroscopy or DA), with and without the patient table and pad in the beam. Calibration files are generated for the frontal and lateral tubes by measuring the ESD per mAs at the interventional reference point with a calibrated ionization chamber and a 20 cm thick by 30×30 cm PMMA phantom. The calibration file values are obtained using a field size corresponding to the 25.4×25.4 cm image size in the detector plane for the two gantries when using the 10 in. mag mode and the minimum SID (90 cm for the frontal and 95 cm for the lateral tube).⁹ This is done to standardize

FIG. 3. Schematics showing setup used for acquiring calibration data with the 20 cm PMMA phantom, as a function of kVp and beam filter used for exposure (a) with the phantom placed on table with pad, and (b) with the phantom exposed laterally without table and pad in the beam path.

the calibration procedure using a setup (see Fig. 3) which closely approximates typical patient imaging geometry for cardiac and abdominal procedures and correction factors are applied when other field sizes are used. The ESD calibration files include backscatter from the phantom which simulates a chest or abdomen and were measured for a single field size. However, for neuroimaging procedures, backscatter from the patient's head is expected to be different due to differences in size, shape, and composition relative to the torso and is expected to change with changes in the entrance field size. Therefore, an additional correction factor was included in Biplane-DTS when used for neuroimaging. To determine this correction factor, the ESD per mAs was measured as a function of the entrance field area using the setup shown in Fig. 4(b) with an SK-150 head phantom (Phantom-Labs, Pacific Northwest X-Ray, Inc., Gresham, OR), which contains a human skull.⁹ Data sets for frontal and lateral projections were acquired for each x-ray tube, both with and without the table and pad in the beam path. ESD per mAs values measured for the different areas are normalized to the values in the calibration files and fit to a semilogarithmic curve of the form " $a \times \ln(\text{area}_{\text{ent}}) + b$," where (a, b) are the fit parameters, and area_{ent} is the beam area at the phantom entrance surface. A table consisting of values of a and b is stored in a configuration

FIG. 4. Setups used for testing the Biplane-DTS accuracy: (a) 2D validation with the 20 cm PMMA phantom. The 6 cm³ PTW ionization chamber was placed beneath the phantom within a recession in a Styrofoam support which holds the phantom above the soft pad. (b) 3D ESD validation with the SK-150 head phantom. The ionization chamber was placed under the head phantom on the entrance surface. (c) 3D validation of dose and spatial distribution of dose using GafChromic film wrapped around the SK-150 head phantom.

file and this semilog equation is then used to determine a correction factor specific to the field area of each exposure pulse for the x-ray tube and beam filter being used.

2.C.1. Correction factors for patient table and pad attenuation

While acquiring x-ray images during the fluoroscopic procedure, the patient may be irradiated with x-rays that either pass through the patient table and pad (frontal projection) or do not (lateral projection). When the beam passes through the table and pad, the primary beam will undergo broad-beam attenuation. The amount of attenuation depends on the x-ray beam quality as well as the table and pad material and thickness. The ESD calibration files for beams passing through the table plus pad are measured for normal incidence of the x-ray beam. For a beam incident on the table surface at a nonperpendicular angle, θ , the correction factor for the transmitted intensity with exponential attenuation is

$$F_{\text{atten}} = \frac{I_{\theta}}{I_N} = \exp[-(\mu_T t_T + \mu_P t_P)(\sec(\theta) - 1)], \quad (1)$$

where μ_T and μ_P are the linear attenuation coefficients, and t_T and t_P are the thickness for the patient table and pad, respectively, and I_N is the transmitted intensity at normal incidence.¹² Thus the ESD at a nonzero angle, θ , can be calculated if $\mu_T t_T + \mu_P t_P$ and the angle θ are known and with the approximation that patient backscatter and table plus pad forward scatter change proportionally with the primary transmitted.

The value of $\mu_T t_T + \mu_P t_P$ was determined by measuring the primary beam transmission of the table and pad as a function of kVp and added filters using an ionization chamber. It is assumed in this correction that the attenuation is exponential and this assumption has been verified by comparing the measured transmission to the transmission calculated using exponential attenuation as a function of the incident angle.¹⁰ Separate data sets of attenuation values were acquired for the two tubes in both fluoroscopic and DA modes.

2.D. System modeling

The two gantries of the biplane imaging system, the patient table, and the patient skin surface are modeled as 3D geometric objects in the Biplane-DTS. A library of 3D human graphics was developed by using MakeHuman™, a third party software.¹³ The graphics exported from the MAKEHUMAN software in the COLLADA format were morphed using another third party software, Blender™ (Stichting Blender Foundation, Amsterdam, the Netherlands).¹⁴ A series of male and female graphic models has been developed which vary in height and weight, and the appropriate model is selected by the user.¹⁵ The same patient graphic library is shared between the Biplane-DTS for neurointerventional procedures and the cardiac DTS. The graphics are then exported and read into custom written MATLAB functions for increasing

the spatial density of the graphic vertices.¹⁶ The average separation between the vertices on the currently used adult patient graphics in the Biplane-DTS is 3 mm.

2.E. Real-time update of geometry

When the CAN module receives a CAN message related to a geometry change, the information in the CAN message is used to update the corresponding variable of the simulated gantry or patient table in the DTS. Any motion in 3D space can be expressed by a set of translations and/or rotations. The DTS uses the updated information to calculate the transformation matrix using OpenGL's built-in functions. Since the two gantries and the patient table are three different objects, a separate transformation matrix is calculated for each of these.

Any spatial transformation applied to the patient table also applies to the patient graphic. A separate transformation matrix is calculated for the patient graphic by using the transformation information of the table and the position of the patient graphic with respect to the patient table. A GUI is available for manual alignment of the patient graphic with the table.

2.E.1. Determination of patient graphic surface within the x-ray beam

To calculate skin dose to the patient graphic, we first need to know the parts of the patient graphic surface that (i) lie within the x-ray beam and (ii) face toward the x-ray source (i.e., are on an entrance surface). The resolution of the patient graphic is variable but each graphic used in the current Biplane-DTS is defined by a set of about 2×10^6 3D vertices.

The normal vector of each vertex is used to determine if a vertex is facing toward the x-ray source (focal spot). The cosine of the angle between this normal and a given x-ray determines which rays are on the entrance versus the exit side of the graphic. Currently dose is only calculated for those graphic vertices on the entrance side, since the dose is considerably higher for those vertices, being closer to the x-ray source and not attenuated by the patient. We implemented the Möller-Trumbore algorithm to determine which patient graphic vertices lie within the x-ray beam and face toward the x-ray source.¹⁷

Biplane-DTS invokes multiple GPU threads, one for each vertex of the patient graphic, that run in parallel to each other and thus reduce the calculation time for millions of vertices to that of a single vertex. Multiple tasks are achieved during each thread's runtime.

If the vertex is deduced to be within the beam, then the same GPU thread also determines if the corresponding vertex-ray passes through the patient table or not. This is done to determine the vertices for which table and pad attenuation correction with angle will be applied during dose calculation. Cumulative dose values of vertices within the beam are compared to determine the peak skin dose within the current field of view (FOV PSD).

2.F. Dose calculation

The Biplane-DTS reads a CAN message for each x-ray pulse generated on the x-ray system. Information in the CAN message is used to identify the gantry of origin of the pulse, along with the kVp, tube current I (mA), and pulse width PW (ms) used for the corresponding pulse. The Biplane-DTS uses this information to determine the appropriate dose calibration factor, $X_{\text{kVp,proj}}$, for that x-ray pulse. Area-corrected reference point entrance skin dose (including backscatter from the patient) values are then calculated by using the following equation:

$$\text{ESD}_{(\text{ref,proj,area})}(\text{mGy}) = X_{(\text{kVp,proj})} \left(\frac{\text{mGy}}{\text{mAs}} \right) \times \frac{\text{PW}(\text{ms})}{1000} \times I(\text{mA}) \times \text{ACF}(\text{area}_{\text{ent}}), \quad (2)$$

where ACF is the area correction factor for the corresponding x-ray tube and the beam filter.⁹

The next step is to calculate the dose for individual graphic vertices by applying an inverse-square distance correction and table and pad attenuation correction for nonperpendicular rays. The values of $\text{ESD}_{(\text{ref,proj,area})}$ are copied to the GPU memory, and the GPU launches a thread for each vertex on the patient graphic. For vertices which have been marked “within the beam” by the Biplane-DTS earlier during geometry updates, absorbed dose to be added is calculated as follows:

$$\Delta \text{Dose}_v(\text{mGy}) = \text{ESD}_{(\text{ref,proj,area})}(\text{mGy}) \times \left(\frac{d_{\text{ref}}}{d_v} \right)^2 \times F_{\text{atten}}, \quad (3)$$

where 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 nonperpendicular to the table given by Eq. (1).

ΔDose_v is added to the previous cumulative value of the vertex dose to get the new cumulative dose value for the corresponding vertex. For graphic display, each vertex is assigned a RGB color by using a dose-correlated color map as shown in Fig. 1. Color calculation for a vertex is done immediately after dose calculation on the same GPU thread that does the dose calculation for the corresponding vertex.

2.G. Estimation of pulse rate (PR) and dose rate

PR is not required for calculating patient skin dose in the Biplane-DTS, but can be used for estimating the dose rate at the patient entrance skin surface. In Biplane-DTS, PR is determined by calculating the time difference between the timestamps on the CAN messages of two consecutive x-ray pulses. The dose rate at the skin surface that is displayed by the DTS is the maximum value determined by multiplying PR by the value of ΔDose_v per pulse calculated from Eq. (3) for the vertex closest to the focal spot.

2.H. Biplane-DTS validation

The ability of Biplane-DTS to accurately calculate the quantitative skin dose values and the spatial scaling of the dose distribution was tested by making exposures on different phantoms, and the Biplane-DTS calculated values were compared against dose values measured with an ionization chamber and with radiosensitive Gafchromic® film [XR-RV3, International Specialty Products (ISP), Wayne, NJ]. The frontal tube with the patient table and pad in the x-ray beam path was used for taking frontal projections, and the lateral tube without the patient table and pad in the x-ray beam path was used for taking the lateral projections, unless otherwise indicated. The accuracy was tested both in 2D using a 20 cm thick PMMA block and in 3D using the SK-150 head phantom. Accuracy for this validation is defined as the agreement of the displayed dose with the dose measured by the ionization chamber or GafChromic film. These measurements may have their own uncertainties in determining skin dose, although we have tried to minimize any such errors.

2.H.1. Comparison with the ionization chamber

A calibrated PTW 6 cm³ ionization chamber (Model TN34069-2.5, PTW, Freiburg, Germany) was used to test the accuracy of the Biplane-DTS in calculating dose rate and integrated dose. Since we are testing the ability of the software system to provide what is defined as the skin dose as measured with the ionization chamber, the same ionization chamber was used for calibration of the software as that used for the validation and the calibration of GafChromic film. This removed any potential differences in chamber response as an additional source of uncertainty in the software validation that might arise if different chambers had been used. The chamber was calibrated at 80 kVp (3.4 mm Al HVL) to provide air kerma within 5%, while the PTW Unidose Webline electrometer used was calibrated with an uncertainty of 0.5%. The chamber has a quoted energy dependence of less than 3% between 50 and 150 kV, complies with IEC 61674, and has “shadow free construction and low attenuation” to have little perturbation of the beam.¹⁸ For all calibration and validation measurements with a phantom, the chamber was placed on the entrance surface. The chamber has a thickness of 10 mm so the center of the sensitive volume is 5 mm from the surface introducing less than 2% systematic error in skin dose determination due to inverse-square variation with distance when at the interventional reference point. For 2D testing with the PMMA phantom, the Biplane-DTS used area correction factors for the PMMA phantom.

For the 2D comparisons, the 20 cm thick PMMA phantom was placed on the patient table with the entrance surface 15 cm tube side of the gantry isocenter for measurements with the frontal tube, and the ionization chamber was placed in the center of the x-ray field next to the phantom entrance surface [see Fig. 4(a)]. So that the PSD reading of the display coincided with the position of the ionization chamber, a 2.5 × 2.5 cm 2D graphic was used to simulate the ionization chamber and positioned on the table top in the Biplane-DTS.

To evaluate the accuracy of the software with variation of kVp, the dose rates and the integrated dose were recorded from the ionization chamber and Biplane-DTS, while making exposures at different kVp's for the four different beam filters available on the machine, using the reference field size (25 cm mag mode). Measurements were made similarly for the lateral projections by rotating the PMMA phantom so as to have the entrance surface in the lateral direction and by using the lateral x-ray tube without the table in the beam.

To test the ability of the system to accurately correct for the changes in field area, the same setup shown in Fig. 4(a) was used for measuring dose values as a function of x-ray beam area at the phantom entrance surface. The integrated dose was recorded from the ionization chamber and Biplane-DTS, while making exposures at 80 kVp for the 1.8 mm Al and the 0.5 mm Cu filters, with different field areas.

To test the accuracy of the table+pad attenuation correction applied in the Biplane-DTS, the integrated dose measured with the ionization chamber was compared to the Biplane-DTS reading at different CRA/CAU and RAO/LAO gantry angles. Exposures were made in DA mode at a fixed technique of 80 kVp, with the 1.8 mm Al added filter. The table position was adjusted to move the ionization chamber to the center of the x-ray beam for each angular position of the gantry.

For testing the Biplane-DTS accuracy in 3D, the ionization chamber was placed in contact with the entrance surface of the SK-150 head; Fig. 4(b) shows the setup with the chamber on the posterior surface under the phantom. A patient graphic with head similar to the SK-150 head phantom was selected from the graphics library and used in the Biplane-DTS. The dose rates and the integrated dose were recorded from the ionization chamber and Biplane-DTS, while making exposures at different kVp's for two different added filters (i.e., 1.8 mm Al and 0.5 mm Cu). Measurements were made similarly for the lateral projection.

To test the accuracy of the area correction factor, the SK-150 head was exposed with the beam collimated to different areas. Data were taken with 1.8 mm Al and 0.5 mm Cu added filters at 80 kVp for the frontal and lateral projections.

2.H.2. Comparison with Gafchromic film

Gafchromic XR-RV3 film was calibrated by placing small strips (2.5 × 2.5 cm) on the patient table and pad under the 20 cm PMMA block and exposing them to a range of different known exposures, determined with the PTW 6-cm³ calibrated ionization chamber placed at the film position under the PMMA as it was for the DTS calibration. The films were scanned with a Canon MX310 scanner (75 DPI, color mode) 24 h after the exposure, and the red channel of the image was used as recommended by Giles and Murphy.¹⁹ All films were exposed and scanned in the same orientation, so as to minimize the error due to the polarization effect of the film.^{20,21} A calibration curve was acquired by plotting the dose versus the respective red channel values²² and fitting the data with a fourth degree polynomial equation which had an r^2 value of 0.99748.

To test the accuracy of the Biplane-DTS in 2D, a sheet of GafChromic film was placed on the patient table with the 20 cm PMMA phantom directly on top, and different areas of the film were exposed with different amounts of radiation, while the Biplane-DTS calculated the distribution of dose on a 2D film graphic.

The 3D Biplane-DTS accuracy was tested by wrapping GafChromic film around the SK-150 head phantom as shown in Fig. 4(c). Different areas of the film were exposed to different amounts of x-radiation using frontal or lateral or biplane projections, while the Biplane-DTS calculated the dose values and spatial distribution on the head of a patient graphic that closely resembled the SK-150 head.

3. RESULTS

3.A. Biplane-DTS calibration

Calibration files were obtained for the frontal and lateral tubes with and without the table plus pad in the beam for the DA and fluoroscopy modes. The data were measured at 10 kVp intervals and fit to a second degree polynomial so that values at each kVp could be interpolated for the calibration file of mGy/mAs values versus kVp. The frontal and lateral x-ray tubes both produced a different exposure per mAs when used in DA mode as compared to the fluoroscopy mode, likely due to differences in x-ray pulse shapes since fluoroscopy mode uses grid control, while DA does not. Figure 5 shows the ratio between the DA and fluoroscopy outputs for the lateral tube without the table and illustrates the error that would be introduced if a single calibration file were used for both. The ratios are filter dependent because of the differential attenuation of the different spectra produced for fluoroscopy and DA.

Figure 6 shows the correction factor to the calibration file data for the SK-150 head phantom with the frontal tube. The data points are the ratio of ESE values measured in fluoroscopy

Fig. 5. Ratio of x-ray output measured in DA mode to x-ray output measured in fluoroscopy mode for the lateral tube without the table in the beam as a function of kVp and different added beam filters.

FIG. 6. Normalized ESD values measured in fluoroscopy mode for the SK-150 head phantom as a function of field area and using the frontal tube (a) with the table and pad in the beam path and (b) without the table and pad. The SK-150 ESE values are normalized to the calibration data acquired with PMMA for the corresponding filter with a reference entrance field size of 240 cm², with or without the table and pad. The solid curves are 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.

mode at 80 kVp for the head phantom as a function of field area normalized to the calibration data acquired at the reference field size with the 20 cm PMMA phantom at 80 kVp for the corresponding filter. The solid curves are log fits used for the calibration files for applying the area and PMMA-to-head correction during dose calculations for neuro procedures.

3.B. Transmission through the patient table and pad

The patient table attenuates the beam by 15%–23%, while the pad reduces the transmitted beam intensity by an additional 5%–10% depending on the kVp and added filter.²³ Transmission data for the lateral tube showed similar results. The ratios of transmitted to primary beam intensity were used to calculate the values of ($\mu_T t_T + \mu_P t_P$) as a function of kVp and added filters. These values are stored in calibration files that are used for the attenuation correction of the nonperpendicular rays.

3.C. Biplane-DTS validation

3.C.1. Comparison with the ionization chamber

The integrated dose and dose rate values calculated by the Biplane-DTS were compared to the values measured with the ionization chamber placed on the entrance surface of the 20 cm PMMA phantom for the range of kVp settings (50–125 kVp) and beam filters available. The ratio of DTS value to ionization chamber reading for the frontal and lateral tubes in fluoroscopy and DA modes ranged between 0.994 and 1.007 for all kVp's and filters for both cumulative dose and dose rate.

Figure 7 shows the ratio of the dose values calculated by the Biplane-DTS to that measured with the ionization chamber

with the PMMA block phantom as a function of entrance beam area and using different added filtrations. Again, the range of ratios was very narrow, being between 0.995 and 1.001 for all field sizes and conditions.

Figure 8 shows the ratio of the dose values calculated by the Biplane-DTS to that measured with the ionization chamber at various combinations of cranial/caudal (CRA/CAU) and right anterior oblique/left anterior oblique (RAO/LAO) angles and using the frontal and lateral tubes. The values are plotted by CRA/CAU or RAO/LAO angle to identify any functional dependence, although the gantry was concurrently angulated in both directions in random combinations. The mean of the ratio increased by about 1% when measuring at non-normal angles, compared to those for which the beam is normal to the table. The ratios over the range of incident angles varied from 0.99 to 1.04.

From the measurements made on the PMMA phantom with a flat surface, it is seen that the Biplane-DTS can calculate skin dose with less than 4% difference compared to the measured dose.

Figure 9 shows the ratios of the integrated dose and the dose rates recorded from the Biplane-DTS and the ionization chamber, while exposing the SK-150 head phantom in frontal and lateral directions at different kVp's and for two added filters in fluoroscopy mode. Similar agreement was obtained in DA mode.

Figure 10 shows the ratios of the integrated dose read from the Biplane-DTS to that recorded from the ionization chamber as a function of entrance field size for the SK-150 head. The mean values and range of the ratios for the two tubes using two different imaging modes and two added filtrations are given in Table I, which shows a maximum range from 0.982 to 1.017.

The graphs in Fig. 11 show the ratios of the dose calculated by the Biplane-DTS to that measured with the ion chamber

FIG. 7. Graphs of the ratios of the dose values calculated by the Biplane-DTS to the values measured with the ionization chamber as a function of entrance beam area for the 20 cm PMMA phantom with different added filters at 80 kVp (a) for frontal projections and (b) for lateral projections.

with the beam placed at various randomly selected locations on the SK-150 phantom. The maximum range of values is from 0.97 to 1.08.

3.C.2. 2D comparison using GafChromic film

The table in Fig. 12(a) shows a comparison of the dose values measured with the GafChromic film at different points shown in the graphic with the values read from Biplane-DTS. As seen in the table, the dose values read from the Biplane-DTS agreed with those measured with GafChromic film within 5% ($\sigma = 2.6\%$). Figure 12(b) shows a comparison of the spatial distribution of dose in Biplane-DTS's virtual film to that measured with GafChromic film, while the table in Fig. 12(b) compares the ratio of the scaled dimensions measured

for each exposed area. This ratio ranged from 0.97 to 1.03 with a standard deviation of 1.9%.

3.C.3. 3D comparison using GafChromic film

3.C.3.a. Comparison using frontal projections only. The table in Fig. 13(a) shows a comparison between measured and calculated dose values at different points labeled A–D on the GafChromic film and DTS graphic. The values in the table indicate that Biplane-DTS calculated skin dose with good agreement to measurements (with $\sigma = 2.2\%$) even in overlapping-beam regions. Figure 13(b) shows the comparison of the spatial distribution of the doses calculated by the Biplane-DTS and measured by the film. There are some irregularities at the beam edges for the DTS due to the vertex

FIG. 8. Graphs of the ratios of the dose values calculated by the Biplane-DTS to the values measured with the ionization chamber, as a function of various gantry angles for two added filters (1.8 mm Al and 0.5 mm Cu), when 20 cm PMMA was exposed for (a) frontal projections and (b) lateral projections.

Fig. 9. Graphs showing the ratio of the dose and dose rate values calculated by Biplane-DTS to the values measured with the ionization chamber, as a function of kVp and added beam filter when the SK-150 head was exposed for (a) frontal projections and (b) lateral x-ray tubes in fluoroscopy mode.

placement on the head graphic which has a large curvature. As shown in the table in Fig. 13(b), when the irregularities are visually averaged, Biplane-DTS mapped the spatial distribution of the skin dose very accurately (with $\sigma = 2\%$).

3.C.3.b. Comparison using lateral projections only. For testing the accuracy of the Biplane-DTS to map the skin dose distribution in the lateral direction, GafChromic film was wrapped around the SK-150 head and exposed to x-rays in the lateral direction using the lateral tube. Figure 14(a) shows the film after different areas of the film were exposed to different amounts of radiation, and the dose map as recorded by the Biplane-DTS on a patient graphic, while the film was being exposed.

The table in Fig. 14(a) shows a comparison of the dose values calculated by the Biplane-DTS and measured by the GafChromic film, at different points (labeled A–D in the

figure). The standard deviation of the ratios was found to be 2.86%, which is slightly higher than in the case of the frontal projections.

Figure 14(b) shows a spatial comparison of the dose maps recorded by the Biplane-DTS and the GafChromic film, for the lateral projections. As seen in the inserted table, Biplane-DTS was able to accurately map the skin dose distribution very accurately (with $\sigma = 1.2\%$).

3.C.3.c. Comparison using biplane projections. GafChromic film wrapped around the SK-150 head was exposed to x-rays for frontal and lateral projections simultaneously. Figure 15(a) shows the GafChromic film after different areas of the film were exposed to radiation, and the screenshot of the Biplane-DTS with the recording of the spatial distribution of dose performed in real-time during the exposure.

Fig. 10. Graphs showing the ratio of the dose values calculated by the Biplane-DTS to the values measured with the ionization chamber, as a function of entrance skin area and added filter when the SK-150 head was exposed for (a) frontal and (b) lateral projections.

TABLE I. The mean and standard deviation as well as the range of the ratios of the integrated dose and dose rate recorded by the Biplane-DTS to that measured with the ionization chamber for the SK-150 head phantom, over a range of skin entrance areas from 80 to 350 cm² and for two different added filters as shown in Fig. 10.

			Dose ratio (biplane-DTS/ionization chamber)	
			1.8 mm Al	0.5 mm Cu
Frontal	Fluoro	Mean	1.014 ± 0.009	1.009 ± 0.013
		Range	1.002–1.031	0.982–1.027
	DA	Mean	1.006 ± 0.011	0.999 ± 0.007
		Range	0.992–1.026	0.989–1.011
Lateral	Fluoro	Mean	1.017 ± 0.010	1.009 ± 0.011
		Range	1.000–1.038	0.991–1.025
	DA	Mean	1.004 ± 0.008	1.004 ± 0.011
		Range	0.988–1.014	0.985–1.018

The table in Fig. 15(a) shows the comparison of dose values read from the film and from the Biplane-DTS graphic, at different points (labeled A–E in the figure). As shown by the values in the table, the ratio of calculated to measured dose ranged from 0.94 to 1.01, while the standard deviation of the ratio of the Biplane-DTS values to the film was found to be 2.94%, indicating very good agreement.

Figure 15(b) shows a comparison of the spatial distribution recorded by the Biplane-DTS and the film from the exposures performed using the biplane imaging mode. Comparison between the dose maps read from the Biplane-DTS and the film again shows excellent spatial correlation. Quantitative comparison of the ratio of distances on the two dose maps had a standard deviation of 1.5% as seen in the table in Fig. 15(b).

4. DISCUSSION

The Biplane-DTS calculates patient skin dose in real-time by collecting data for the individual exposure pulses from

both x-ray tubes on the imaging system, and the color-coded graphic display is updated immediately after dose calculation. By using the parallel processing power of the GPU, the DTS can do a large number of calculations in real-time and display the skin dose map to the physician without any observable lag. The current version of the Biplane-DTS updates the display screen every 30 ms, thereby providing real-time feedback to the physician. A useful feature of the DTS is the display of the FOV PSD, so the operator is aware of the maximum dose value at the current location of the beam. This value is provided as the gantry, and the virtual beam is panned over the patient and collimated as an aid so that dose spreading can be used to avoid high dose due to overlap of beam projections. The higher the resolution of the graphic the more precisely the beam projection can be defined and the more precise the dose spreading can be.

The skin dose includes contributions from primary radiation, backscatter radiation, and forward scatter from the patient support when in the beam. Since this system relies on a calculated dose value, the calibration factor is determined to include all of these factors. The backscatter component in the calibration factor depends somewhat on the phantom used for the calibration. For cardiac procedures, we have used both PMMA and solid water and found a difference of about 10%.²³ For neurointerventional procedures, the DTS employs a separate correction factor for the head, which is included in the area correction factor. Differences up to 12% were found for different head-simulating phantoms.²³ It was assumed that the head phantom with a human skull most closely matches the backscatter for a patient head and Biplane-DTS uses the appropriate correction factor based on the SK-150 phantom when calculating skin dose to the head.

We have also assumed that the x-ray tube output varies linearly with the mAs, which is true for the mAs ranges used with the Toshiba Infinix system in the clinic. However, additional correction may be required while calculating dose

FIG. 11. Graphs showing the ratios of the integrated dose calculated by the Biplane-DTS to the values measured with the ionization chamber at various randomly selected positions on the SK-150 head phantom for (a) frontal projections and (b) lateral projections.

FIG. 12. (a) Comparison of the dose measured by a sheet of GafChromic film (i) that was exposed under the PMAA block phantom with the dose calculated and displayed by Biplane-DTS on a virtual 2D film (ii). The dose values for the letter identified regions are compared in the table. (b) A comparison of the spatial distribution of dose as calculated on the Biplane-DTS virtual film and as recorded on the GafChromic film. The normalized ratio of the dimensions indicated by the arrows is compared between the DTS display and the Gafchromic film in the table.

if the tube output shows nonlinear dependence on the mAs and a functional dependence could be added to the software.

Accuracy of the dose calculated with the Biplane-DTS depends on the size, shape, and position of the graphics used for simulating the patient skin surface, as these factors will affect the inverse square distance correction and area correction factor used in the dose calculations. Thus, the graphic should be carefully chosen and positioned in the Biplane-DTS to represent the patient skin surface as accurately as possible. The current system uses a library of patient

graphics with varying weight and height for male and female shapes from which the best match to the patient is selected. The graphic has a default position with the head aligned with the top of the table and the torso laterally centered, and positioned at the top of the pad. The GUI allows user adjustment of the position by input of distance (cm) values or by dragging the patient graphic. This can be done at any time during the procedure if there were to be a change in patient position. However, the error typically should be small due to inverse-square difference in exposure due to misplacement of

FIG. 13. (a) Comparison of the dose measured by a sheet of GafChromic film (upper left) that was exposed under the PMAA block phantom with the dose calculated and displayed by Biplane-DTS on a virtual 2D film (upper right). The dose values for the letter identified regions are compared in the table. (b) A comparison of the spatial distribution of dose as calculated on the Biplane-DTS virtual film and as recorded on the GafChromic film. The normalized ratio of the dimensions indicated by the arrows is compared between the DTS display and the Gafchromic film in the table.

FIG. 14. (a) Comparison of the dose measured by a GafChromic film that was wrapped around the SK-150 head with the Biplane-DTS displayed cumulative dose distribution following exposure with the lateral tube. The dose values for the letter identified regions are compared in the table. (b) A comparison of the spatial distribution of dose for lateral projections. The normalized ratio of the dimensions indicated by the arrows is compared between the DTS display and the Gafchromic film in the table.

the graphic. A one cm discrepancy would result in less than 5% error when 15 cm tube-side of isocenter.¹² If the graphic were not positioned correctly relative to the beam position but still intercepted the beam, the entire dose distribution would still be spatially accurate but displaced on the skin surface. This displacement would have most significance when trying to spatially match the dose distribution of subsequent procedures but would have little impact on the peak skin dose determination for the current procedure.

Our goal in designing the DTS software has been to make the estimate of skin dose and its distribution as accurate as possible, so informed decisions can be made by the physician with confidence in the dose values during the procedure. The decision on how to use this information would be based on the physician's perception of risk versus benefit to the patient. Although threshold dose values have been defined for various deterministic effects and can provide guidance, the actual risk

for the individual patient may not be predictable because of variability of skin response.²⁴

The patient table and pad have a measurable effect on the beam intensity at the patient's skin. Included in this effect is both beam attenuation and beam forward scatter. The DTS calibration files for those rays passing through the table include both of these effects at normal incidence. A correction factor for rays at non-normal incidence is estimated with the assumptions that attenuation is exponential and that the table scatter is proportional to the intensity of the transmitted beam. These assumptions were validated by the close agreement of the measured and calculated results for frontal projections especially those of Fig. 8(a), which show the dose ratio with the table and pad in the beam to be uncorrelated to gantry angle; these results substantiate those of previous measurements of transmission versus angle.¹⁰ The patient table and pad attenuation depend on the beam quality (kVp

FIG. 15. (a) Comparison of the dose measured by a GafChromic film that was wrapped around the SK-150 head with the Biplane-DTS displayed cumulative dose distribution following exposure with the frontal and lateral tubes using the Biplane imaging mode. The dose values for the letter-identified regions are compared in the table. (b) A comparison of the spatial distribution of dose as calculated on the Biplane-DTS film and as recorded on the GafChromic film. The normalized ratio of the dimensions indicated by the arrows is compared between the DTS display and the Gafchromic film in the table.

and added beam filter used), and thus, separate correction files have been included in the Biplane-DTS which provide the attenuation coefficient parameters as a function of kVp for the different added beam filters available on the C-arm system.

The agreement of Biplane-DTS calculated 3D patient skin dose with the measured values was slightly better for the frontal projections than the lateral projections. This difference can be explained on the basis of the mismatch between the patient graphic and the film position on the lateral side. Because of the presence of the ears on the SK-150 head, it is not possible to wrap the film completely in contact with the head phantom. Also, we selected a patient graphic from the DTS graphics library that was judged to closely match the head phantom surface, but it was not necessarily identical to the head phantom. Mismatch between the shapes of the head and the graphic and the method of wrapping the film could lead to increased differences between the dose values read from the film and those calculated by the Biplane-DTS.

For this version of the Biplane-DTS, calibration was performed by measuring dose in the center of the beam, and the dose calculation assumed that the beam intensity is uniform over the field. However, skin dose values near the edge of the beam are expected to be different from the central values because of the Heel effect and the variation in scatter across the field and this can introduce some error.²²

Rather than using the data provided by the manufacturer's CAN bus, the DTS software could be adapted to use the data provided by the DICOM RDSR as others have done.^{25,26} In that case, the air kerma value provided by the RDSR would need to be validated and spectrum-dependent correction factors for patient backscatter as well as for table attenuation and scatter would need to be applied. The DTS as currently designed uses a calibration file that includes measured backscatter and table attenuation and scatter that is specific for the spectra of the individual machine. The RDSR would not allow tracking of compensation or ROI filters (as able to be done with the CAN bus) and the dose would be overestimated if these were not accounted for. In addition, the RDSR includes air kerma values for exposure events rather than individual x-ray pulses and this could cause misplacement of the skin dose if the beam were moved during the event. Finally, the RDSR is currently not available as streaming data during the procedure and the skin dose distribution would not be available in real-time.

5. CONCLUSIONS

We have developed a real-time dose tracking system (Biplane-DTS) that can acquire and identify geometry and exposure parameters from a Toshiba Infinix Biplane™ system during neurointerventional fluoroscopic procedures and use these data to calculate patient skin dose. The calculated dose can be displayed as 3D color maps on human graphic models showing the frontal and lateral projections of a biplane imaging system for immediate feedback to the physician. The peak skin dose at any point on the patient graphic is simultaneously numerically displayed to aid in dose

management. The accuracy of the system has been validated on phantoms using both ionization chamber and Gafchromic film measurements.

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CONFLICT OF INTEREST DISCLOSURE

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