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Use of a graphics processing unit (GPU) to facilitate real-time 3D graphic presentation of the patient skin-dose distribution during fluoroscopic interventional procedures

Vijay Rana*, Stephen Rudin, and Daniel R. Bednarek

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

Abstract

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 from the digital bus on a Toshiba Infinix C-arm unit. The cumulative dose values are then displayed as a color map on an OpenGL-based 3D graphic of the patient for immediate feedback to the interventionalist. Determination of those elements on the surface of the patient 3D-graphic that intersect the beam and calculation of the dose for these elements in real time demands fast computation. Reducing the size of the elements results in more computation load on the computer processor and therefore a tradeoff occurs between the resolution of the patient graphic and the real-time performance of the DTS. The speed of the DTS for calculating dose to the skin is limited by the central processing unit (CPU) and can be improved by using the parallel processing power of a graphics processing unit (GPU). Here, we compare the performance speed of GPU-based DTS software to that of the current CPU-based software as a function of the resolution of the patient graphics. Results show a tremendous improvement in speed using the GPU. While an increase in the spatial resolution of the patient graphics resulted in slowing down the computational speed of the DTS on the CPU, the speed of the GPU-based DTS was hardly affected. This GPU-based DTS can be a powerful tool for providing accurate, real-time feedback about patient skin-dose to physicians while performing interventional procedures.

Keywords

skin dose; dosimetry; fluoroscopic dose; dose tracking; real-time dosimetry; fluoroscopic interventional procedures; GPU

1. INTRODUCTION

X-ray fluoroscopic image-guided interventional procedures are becoming widespread and longer in duration, thereby resulting in an increase in the amount of ionizing radiation being delivered to patients and in an increased risk of deterministic skin effects.^{1–4} 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 and imaging-system-geometry parameters from the digital bus on a Toshiba Infinix C-arm unit.^{5, 6} The cumulative dose value is displayed as shown in Fig. 1 as a color map on an OpenGL-based 3D graphic of the patient which consists of a 3D mesh of triangular elements. In the current version of the DTS, human graphic models from the CAESAR anthropomorphic project⁷ are used to

represent the patient graphic in the DTS. In this paper we investigate the ability of a GPU to increase the computational speed of the DTS software so that the resolution of the patient graphic can be improved without introducing lag in the real-time update of the skin dose distribution in the display.

The DTS acquires the exposure parameters and imaging-system-geometry parameters from the digital bus on a Toshiba Infinix C-arm unit, and then calculates the dose delivered to the patient's skin based on the acquired parameters. This calculation has been shown to be accurate within 5% by verification with ionization chamber and GafChromic film measurements.⁸ The speed of the DTS software depends on the speed of data acquisition and on the speed of the dose calculations. The parameter acquisition part of the software is limited by the rate of data transfer between the digital bus and DTS computer, whereas the dose calculation part depends on various factors, including the processing speed of the computer, the number of elements (small 3D triangles) constituting the patient graphic and the x-ray beam size at the patient surface. In addition, the geometric agreement between the beam shape and the patient graphic depiction depends on the element size, i.e., the smaller the element size, the higher is the spatial resolution on the patient graphic and hence the better is the geometric agreement (see Fig. 2).

Higher resolution can be achieved by subdividing the graphic elements into smaller elements, which also results in an increase in the number of elements in the patient graphic. But increasing the number of elements results in an increase in the computational load and eventually slows down the real-time performance of the DTS.

In order to increase the resolution of the patient graphic without compromising the speed performance of the software, the parallel processing power of the GPU can be harnessed for dose calculations in the DTS. In this study we present a comparison between the performances of a GPU-based DTS and a CPU-based DTS, as a function of the patient graphic resolution.

2. MATERIAL AND METHODS

The DTS is connected to the CAN bus on a TOSHIBA Infinix C-arm unit and reads the geometry and exposure parameters as data packets, while the procedure is being performed by the physician. This permits the real-time calculation of the skin dose at each point on the patient's entrance surface.

2.1 Geometry Calculations

Geometry parameters read from the CAN bus include the degrees of freedom for the patient-table and gantry, the collimator position and SID. If the DTS reads a change in the geometry parameters, the elements on the patient graphic that intersect the beam are determined and saved in a temporary buffer. The DTS also calculates and stores the distance of the x-ray source from each of the intersecting elements in order to apply an inverse-square correction when calculating the dose when an exposure is made. The current version of the DTS determines those elements within the beam by computing the intersection of the x-ray beam with each point on the patient graphic and determining if it is within the beam. The geometric agreement of the x-ray beam shape with its graphic representation improves with increasing resolution of the DTS patient graphic. Therefore, in order to better delineate the x-ray beam on the graphic, each triangle on the patient graphic was sub-divided into smaller triangles by inserting additional vertices at the midpoints of the sides of the triangles as show in Fig. 3. Since an increase in the number of graphic elements increases the number of calculations and computational time for the CPU, there is a tradeoff between the graphic resolution and the real-time performance of the DTS.

2.2 Dose Calculations

Exposure parameters read by the DTS from the CAN bus include kVp, mA, pulse width, imaging mode (e.g., pulsed fluoroscopy, digital acquisition, continuous fluoroscopy), and beam filter being used. Based on these parameters, the DTS calculates the dose to the intersecting elements by using calibration files that provide the skin dose including backscatter per mAs at a reference point as a function of beam kVp and filter. Inverse-square distance correction is applied for calculating the dose to each of the intersecting points. The DTS also applies a correction for the variation of the attenuation of the patient table for each surface element due to the variation of the angle of transmission of the beam through the table to that element on the patient graphic (see Fig. 4).

The effective table thickness for an element can be calculated by using the formula:

$$T' = T(\tan^2(\alpha) + \tan^2(\beta) + 1)^{1/2} \quad (1)$$

where T' is the effective table thickness, T is actual table thickness, α is the angle in the RAO/LAO direction and β is the angle in the CRA/CAU direction, as shown in Fig. 4. The corrected dose rate at the element is then given by:

$$DR_{Corrected} = DR_{\perp} e^{-\mu T (\frac{T'}{T} - 1)} \quad (2)$$

where $DR_{\perp}$ is the dose rate with normal incidence to the table, μT is the product of table attenuation coefficient and thickness with normal incidence determined from transmission measurements and the ratio $\frac{T'}{T}$ is obtained from Eq.1.

The flowchart in Fig. 5 shows the basic steps of the DTS for calculating the skin dose to a patient in real time during a clinical procedure and then displaying the dose as a 3D patient graphic.

Whenever the geometry of the physical system is changed (e.g. patient table is moved), a message is sent through the CAN bus from the x-ray machine, which is then read by the DTS. The DTS then performs the corresponding 3D calculations and determines which patient-graphic elements intersect with the x-ray beam by calculating the geometry of every element in the patient graphic, one-by-one, with respect to the x-ray beam geometry. The DTS graphic display window is then updated with the changes. Similarly when an exposure is made, the DTS reads the corresponding message from the CAN bus and calculates the dose being delivered to the patient graphic elements that intersect the beam. For calculation of the dose, the DTS first calculates the exposure at the reference point using the currently selected technique parameters and the calibration file data. The DTS then calculates the dose increment to intersecting elements by applying the inverse-square-distance and table-attenuation corrections for each of the intersecting elements, one-by-one. The total dose to each intersecting element is calculated and an RGB color is assigned which corresponds to the cumulative dose to that particular element. Because the dose calculations are made by the CPU for all the intersecting elements, one at a time, a lag may be introduced between the actual time of data acquisition and the time of display on the DTS screen. The higher the number of intersecting elements, the greater is the temporal lag. Therefore, for the DTS display to be able to be updated in real time, either a graphic with a smaller number of larger elements (low resolution graphic) has to be used so that, for any given exposure, a small number of calculations has to be performed by the computer processor, or a computer with a tremendous processing speed has to be used which can perform a huge number of dose calculations in real time. The former option is not desirable because of the poor beam graphic definition obtained.

To speed up the processing so that the patient graphic resolution can be improved in order to calculate the dose distribution to the patient more accurately and in real time, we developed a GPU-based version of the DTS which uses the parallel computing power of the GPU. The CPU-based DTS software was run on a system with an Intel Pentium 2.26 GHz Core 2 Duo processor, while the GPU-based DTS calculations were performed on a system installed with an NVIDIA GeForce GT 540M GPU card. C++ and OpenGL were used for programming the two versions of the dose tracking system. A simulated set of exposure and image-system geometry parameters was passed to each of the DTS programs in order to calculate the dose being delivered to the patient's skin, using a projected beam area of 8 cm $\times$ 8 cm at the patient's back which is typical for a cardiac procedure with a 20 $\times$ 20 cm flat panel fluoroscopic system; this area corresponds to about 145 graphic elements intersecting the beam for the 1x resolution patient graphic. The dose was then displayed as a color map as shown in figure 1. The times taken for dose calculations and displaying the calculated dose as the color map on the 3D patient graphics were determined by using the built-in timer functions in C++. The original resolution of the patient graphic was limited by the tessellation process in which the element size is inversely related to the curvature of the surface. The spatial resolution of the patient graphic was subsequently improved by subdividing each triangular element of the 3D graphic into four elements, and the dose calculations were repeated. The whole procedure of subdividing each element into 4 elements was repeated 3 times, so as to have 4 times, 16 times and 64 times the number of graphic elements in subsequent steps. In each case, the projected beam area at the patient's back was kept the same.

In the GPU-based DTS, an increase in the patient graphic resolution, and hence an increase in the number of dose calculations, was compensated for by using the parallel processing power of the GPU where the dose calculations are performed in groups of a large number of elements at a time such that the calculations for each element are done on a separate core of the GPU at the same time. In this way the time required for a large number of calculations, which are done one element at a time in the CPU-based DTS, is reduced almost to that of a single-element calculation in the GPU-based DTS. The flowchart in Fig. 6 shows how the repetitive part of the exposure calculations in the CPU-based DTS (see Fig. 5) is replaced by a single execution in the GPU-based DTS.

3. RESULTS

Figure 7 shows a comparison of the performance speed of the CPU- based DTS and GPU-based DTS at various resolutions of the patient graphic. As the number of graphic elements increased from the current value (taken as 1X) to 64X, the time taken by the CPU-based DTS for dose calculations also increased drastically, which would hinder the real-time performance of the DTS. On the other hand, the time taken by the GPU-based DTS for performing the same number of dose calculations increased only by a small amount with increasing resolution, but was always less than 30 ms (increasing from about 7 ms to about 26 ms for an increase in the number of graphic elements from 1x to 64x as seen in Fig. 7). In all cases, the GPU-based DTS performed much faster than the CPU-based DTS.

4. CONCLUSIONS

From our results it is clear that the GPU-based DTS performs much faster than the CPU-based DTS, for all resolutions of the patient graphic. Also, with an increase in the spatial resolution of the patient graphic, the computational speed of the GPU-based DTS is not heavily affected. Thus an improvement in patient-graphic resolution, and hence a better representation of the dose mapping and more accurate determination of the integrated dose for overlapping beam segments, can be achieved without compromising the real-time

performance of the dose tracking system. Thus, a GPU-based DTS can be a powerful tool for providing accurate, real-time feedback about the patient's skin-dose distribution to physicians while performing interventional procedures.

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Figure 1. Screenshot of the Dose Tracking System display during a cardiac catheterization procedure being performed on a 72 year old male patient.

Figure 2.

(a) Screen capture showing the geometric agreement between the x-ray beam (region inside the dashed red rectangle) and a low resolution DTS graphic (3D mesh of triangles). (b) Screen capture showing the patient graphic from (a), but at a higher resolution which was achieved by subdividing each graphic element into 16 elements.

Figure 3.

Schematic showing how the patient graphic resolution can be improved by subdividing the triangular elements comprising the graphic. Starting with the default resolution of 1x in (a), new vertices are inserted at the midpoint of each side of the triangular element, resulting in 4 smaller triangular elements, as seen in (b). These sub-elements were similarly subdivided to give 16x resolution (c), and further subdivided to get 64x resolution (d).

T = Table thickness

T' = effective table thickness

Figure 4.

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

Figure 5.

Flowchart showing the steps of the DTS for acquiring the geometry and exposure parameters from the CAN bus on a TOSHIBA Infinix C-arm unit and calculating the skin dose to the patient graphic in real time. The steps outlined by the red dotted line correspond to the real-time determination of exposure at the reference point and calculation of dose delivered, with the inverse square distance correction and the table attenuation correction, to the patient graphic elements which intersect the beam.

Figure 6.

Flowchart showing the steps of the DTS for acquiring the geometry and exposure parameters from the CAN bus on a TOSHIBA Infinix C-arm unit and calculating the skin dose to the patient graphic in real time. The steps outlined by the red dotted line correspond to the real-time determination of exposure at the reference point and calculation of dose delivered, with the inverse square distance correction and the table attenuation correction, to the patient graphic elements which intersect the beam.

Figure 7. A comparison of the time taken for DTS dose calculations at various resolutions of the patient graphic using the CPU and the GPU.