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# SIScaR-GPU: fast simulation and visualization of intraoperative scattered radiation to support radiation protection training

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**Abstract.** Scattered radiation caused by the intraoperative use of mobile image intensifier systems (referred to as "C-arms") is the main source of radiation exposure for operating room personnel and surgeons. To keep this possibly harmful exposure at a minimum level, a deliberate use of radiation, knowledge about distribution of scattered radiation and appropriate behavior pattern are indispensable. Therefore in several countries knowledge concerning these aspects is taught in mandatory courses on radiation protection. Currently this teaching is typically based on non-interactive didactical methods (texts, pictures and videos). Because of the complexity of the knowledge field this restriction might lead to an insufficient understanding of the facts, an inappropriate behavior and therefore to an avoidable radiation exposure. This paper presents a new software module, which is able to simulate and visualize intraoperative radiation distribution and the resulting dose values for the attending persons within a few seconds (less than 30s). The developed components, which simulate the radiation transport using a graphics processing unit three times faster than comparable approaches, were integrated exemplarily in the computer based C-arm training system virtX. This extended training system improves the teaching through a prompt visual feedback on non-trivial scattered radiation facts in freely adoptable situations.

**Keywords.** Scattered radiation, Monte Carlo method, stream processing, CUDA, computer based training, radiation protection

## Introduction

The operative use of mobile image intensifier systems, called C-arms because of the C-shaped arrangement of the emitter and detector, has developed into an essential diagnostic tool in the treatment of emergency and trauma patients. Particularly the growing number of minimal invasive interventions in the past years has increased in addition the use of C-arms during surgery. However, each employment of these mobile X-ray de-

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vices exposes the attending persons to potentially harmful radiation. Especially for the personnel, which often cannot leave the operating room (OR) during X-ray examination, the frequent use of the C-arm during their daily work leads to a constantly growing radiation exposure. The biggest amount of this exposure is caused by scattered radiation [1]. The energy spectrum, the intensity and the spatial distribution of the scattered radiation are a function of numerous factors: the composition and geometry of the irradiated material, the spectrum and intensity of the primary beam as well as its geometry and direction. Because of this complexity, areas with high radiation exposure are not intuitively predictable. Technical enhancements of C-arms and the use of radiation protection equipment reduce the radiation exposure for the affected group of persons. However, the resulting individual dose rate primarily depends on the deliberate use of radiation, the correct adjustment of the C-arm and the knowledge about the complex behavior of scattered radiation. To keep the radiation hazard for the attending persons as low as possible, in several countries the latter information is taught in courses on radiation protection. Currently the teaching in these courses is mostly based on texts, schematic pictures and videos. This restriction to non-interactive teaching material might lead to an insufficient understanding of the complex effects of scattered radiation and its spatial distribution. This in turn might lead to an inappropriate behavior of the personnel and hence to an avoidable radiation exposure.

To support the education in courses on radiation protection, an interactive and fast simulation and visualization of the intraoperative scattered radiation named SIScaR-GPU (fast **S**imulation and visualization of **I**ntraoperative **Sca**ttered **R**adiation using **G**raphics **P**rocessing **U**nits) was developed and integrated exemplarily in the computer based training (CBT) system virtX [2].

## 1. Methods

The simulation of the distribution respectively the intensity of scattered radiation and the resulting dose values are usually based on Monte Carlo (MC) methods, which are considered as a gold standard for these applications [3]. With general purpose MC toolkits like GEANT4 [4] or PENELOPE [5] it is possible to simulate the passage of particles through matter by calculating iteratively trajectories of single photons and their interactions with the atoms of the irradiated materials. Via determining a vast number of photon histories the radiation distribution and deposited energies are approximated for a particular simulation setup. This leads to the biggest drawback of MC simulation methods: high computational complexity implicating long calculation times. As already presented by the authors in [5], it is possible to calculate the intraoperative scattered radiation using the GEANT4 toolkit. However, using this toolkit to achieve an acceptable approximation produces calculation times that are too long for an application during interactive lectures.

To speed up the radiation transport simulation we adapted the MC-GPU v.1.1 simulation code [7]. MC-GPU uses CUDA [8] and methods of the PENELOPE 2006 package to calculate photon histories in a voxelized simulation volume in parallel on the graphics processing unit (GPU). To fit MC-GPU to our purpose, the simulation algorithm was modified and extended with several features.

Functions were added to protocol the deposited energies per voxel. Using these procedures the local intensities of scattered radiation within the simulation volume can be estimated.

The simulation of the radiation source was edited to represent a C-arm typical cone beam with adjustable tube voltage and corresponding X-ray spectrum. To generate sample X-ray spectra for tube voltages between 30 and 140 kV the TASMIP [9] program was used. A function was added that allows inserting collimators (iris and slit) to the radiation source.

To dynamically setup an OR scenario in the voxelized simulation volume, an algorithm was implemented, which inserts the material and density values of up to five persons with their radiation protection equipment, a patient, a C-arm and an OR table into the corresponding voxel representation of the volume. To calculate the material and density values of the patient, the personnel and the remaining objects the algorithm utilizes user specified geometrical, position and rotation values of each object or person in the virtual OR, parameters of the selected protection clothes and CT datasets.

To determine the individual body and organ doses of the attending persons in the OR, label volumes were generated for all deployed CT datasets. An algorithm combines these labels and an identifier for the employee or the patient with the material information of the related voxels in the simulation volume. During the simulation procedure the deposited energies in these marked voxels are added to the organ doses of the specified person.

For simulating the automatic dose rate control (ADRC), specific voxels of the virtual C-arm geometry are marked for individual radiation measurement during the setup of the simulation scene. Using the non-scattered photon flux of these voxels, a closed control loop, which controls the number of emitted photons, was modeled and integrated in the simulation algorithm.

As the execution time of the extended simulation process was still not satisfactory for the application during lectures, the algorithm was further optimized. After this fine tuning, a reasonable trade-off between the quality of the approximation and execution time of the algorithm was chosen.

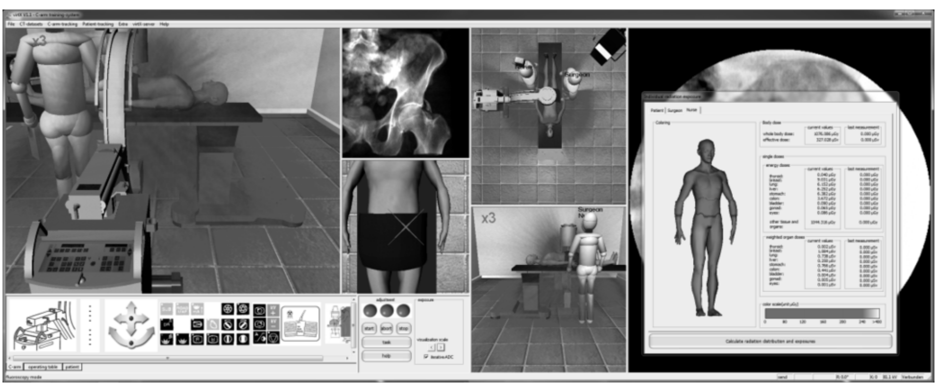

**Figure 1.** Visualization of the simulated scattered radiation and dosage values (left member of the staff) for an anterior-posterior view of the left hip joint with a tube voltage of 80kV.

To illustrate the distribution and intensity of the simulated scattered radiation, a volume visualization of the calculated local dose values was implemented. This visualization maps the dose value of each voxel to a color and transparency value using a transfer function and renders an image employing the VolumeViz extension of the Open Inventor toolkit [10]. To visualize the individual dose values of the attending persons, a spinning human surface model is generated. This surface model is divided into different body regions, each linked to single organ doses. According to the quantity of the simulated doses the corresponding surface areas are colored using a thermography color scale: from violet and blue for low radiation doses via turquoise, green and yellow for medium doses to red and white for high radiation doses.

To evaluate the new simulation and visualization modules, named SIScaR-GPU, they were integrated into the CBT system virtX [2]. This software offers a virtual environment for the task based training of correct C-arm handling. Using graphical control elements or tracked real devices the software enables the user to navigate 3D models of a C-arm, a patient and an OR table in a virtual OR scenario. Using CT datasets virtX is able to generate digital reconstructed radiographs for arbitrary C-arm settings and herby offers a visual feedback for the trainee without radiation exposure. To use the SIScaR-GPU modules in combination with virtX, models of the OR personnel, whose radiation protection clothes can be adopted through graphical control elements, had to be added to the virtual scene. The parameters of all objects in the virtual OR of virtX, including the CT datasets from the radiograph simulation, are preprocessed and transferred to the algorithm of SIScaR-GPU. The volumetric visualization of the simulation results was directly embedded in the representation of the virtual OR (comp. figure 1).

**Table 1.** Execution times of the radiation transport simulation and number of simulated photon histories for different surgical scenarios in the virtual OR of the extended virtX system.

| surgical scenario | no. simulated photon histories ($\cdot 10^6$) | execution time (s) |
|---|---|---|
| pelvis anterior-posterior (a.-p.) | 20.16 | 7.1 |
| pelvis inlet view | 69.12 | 18.8 |
| pelvis outlet view | 86.4 | 28.2 |
| hip joint ala view | 74.88 | 26.4 |
| hip joint obturator view | 112.32 | 29.7 |
| knee joint a.-p. | 5.76 | 1.7 |
| ankle joint a.-p. 20° internal rotation | 8.64 | 2.8 |
| shoulder true a.-p. | 2.88 | 1.6 |

## 2. Results

To quantify the achieved speedup, the execution times needed to simulate $9.6 \cdot 10^7$ photon histories in a 300x300x300 voxelized water volume (tube voltage 80kV, source position (0,40,0), beam direction (0,1,0)) were measured. Data collection was done for three different simulation settings: iterative calculation on one core of an Intel Core i5 K 655 CPU, parallel calculation with the non-optimized algorithm on a Zotac GeForce GTX 480 and parallel calculation with SIScaR-GPU on the same graphics card. The execution time for the iterative simulation on the CPU was measured with 781.7s. The parallel non-optimized photon history simulation took 24.7s, whereas SIScaR-GPU needed only 8.1s. Basing on these values, the speedup of the non-optimized parallel simulation compared to an execution on the CPU could be stated as 31.6-fold, which is near the reported 27 speedup factor of MC-GPU [7]. Through SIScaR-GPU the parallel simulation on the GPU was accelerated by an additional factor of 3.0, which leads to a 96.5-fold speedup compared to an iterative calculation on the CPU. Examinations of the deviations in the calculated photon flux values, which are caused by the changes in the simulation algorithm, showed a very small and for the intended teaching purposes acceptable mean error of 0.066%.

To analyze the effect of the ADRC and heterogeneous simulation volumes on the execution times the radiation values for different surgical OR situations were simulated and visualized using the extend virtX system. The analysis was based on a tube voltage of 80kV and calculated with the already introduced GPU (comp. table 1). Simulation runs were carried out without virtual OR personnel, which would have reduced the measured execution time by absorbing certain photons. The simulation volume that represents the virtual OR of virtX was set to 500x150x350 voxel. The time needed to setup the simulation volume and to display the radiation results was in each case 0.3s.

## 3. Discussion

After optimizing previous approaches SIScaR-GPU is now able to calculate an intuitive and physically correct visualization of scattered radiation distribution in a time span suitable for teaching purposes. Through the simulation of X-ray spectra, collimators and the ADRC the level of realism of the simulation was further enhanced. In addition SIScaR-GPU offers for the first time the possibility to interactively simulate the radiation exposure for the personnel in an OR with different kinds of radiation protection equipment. Whether this new teaching and training tool is able to impart the knowledge concerning scattered radiation better than classical media will be evaluated in upcoming studies. In addition the simulated spatial radiation values should be reviewed using 3D radiation measurements in a clinical setup, because currently they can only be compared to 2D data (isodose curves) of C-arm applications from literature.

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