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An approach to simulate and visualize intraoperative scattered radiation exposure to improve radiation protection training

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Abstract

Intraoperative radiography based on mobile image intensifier systems (C-arms) is widely used during the treatment of trauma and emergency patients. These devices produce scattered radiation, potential hazardous for surgeon and operation room personal (ORP). The propagation and intensity of scattered radiation is not intuitive, is not perceivable by human senses and depends on many variables. At courses on radiation protection the knowledge of the behavior of scattered radiation and the modus operandi to minimize the radiation exposure should be taught to ORP and surgeons. Currently this can only be done theoretically using fixed pictures and precalculated videos. This paper presents an approach to interactively simulate and visualize scattered radiation with a computer based training system for mobile image intensifier systems. The simulation depicts radiation propagation and intensity for arbitrary C-arm adjustments and different irradiated materials. This teaching component focuses on improving the current radiation protection training with interactive visual and practical aspects.

Keywords:

Scattering, Radiation, Computer simulation, Imaging, Three-Dimensional, Education, Radiation protection, Radiography, Interventional

Introduction

During surgical treatment of human and veterinary trauma and emergency patients or in catheterization laboratories mobile image intensifier systems (so called C-arms) are widely deployed to produce intraoperative radiographs. These radiographs are used for controlling, monitoring or documentation purposes during the intervention. Using C-arms the surgical outcome can be enhanced and by this the number of follow-up operations can be reduced. Due to the mobility of a C-arm, achieved by mounting the radiation source and the image intensifier on a freely movable C-construction (see Figure 1), one can create radiographs from every point and viewing angle around the narcotized patient. But this freedom in movement leads to the problem that radiation shielding arrangements, well known from stationary X-ray devices, are very hard or even impossible to install. Beyond that the surgeon, respectively the operation room personal (ORP) cannot leave the operation theatre (OR) during the radiograph generation process, as it is mandatory for stationary X-ray devices. Hence the staff in the OR is frequently exposed to radiation. The biggest amount of this exposure for surgeon and ORP is caused by scattered or so called stray radiation [1, 2]. The scattered radiation is emitted by the irradiated area of the patient every time a radiograph is generated and spreads in all spatial directions. The propagation and intensity of this radiation depends on many variables, for example the intensity and direction of the primary beam, the density values of the irradiated materials and the positioning and type of different objects in the OR [3]. Therefore the prediction and understanding of scattered radiation behavior is not intuitive. In spite of mandatory radiation protection clothes there is still a permanent stochastic risk for the staff regarding radiation injuries through the frequent radiation exposure. Thus to minimize the radiation exposure for all persons in the OR it is necessary that the surgeon and the ORP are able to position and adjust the mobile image intensifier correctly to get a meaningful radiograph with a minimum of scattered radiation. This implies that they understand the behavior of scattered radiation and that they know where regions of high radiation doses for certain adjustment situations are located, so they can take the safest position during the radiograph generation process. This knowledge about scattered radiation is usually presented to ORP and surgeons in courses on radiation protection. In Germany and other countries ORP have to visit these courses by law. Due to the fact that training with real radiation is potentially dangerous, which makes it prohibitive, and that radiation itself could not be perceived by any human sense presentation and education of the knowledge on how to diminish scattered radiation exposure during these courses is only done in a very theoretical way with images, textbooks or precomputed videos. Here the question arises if it is possible to enhance the radiation protection courses with interactive simulation and visualization of scattered radiation embedded in a computer based training system to be able to demonstrate the complex correlations in a practical and visual way.

This paper demonstrates an approach to simulate and visualize scattered radiation for the mentioned training purposes during radiation protection courses.

Materials and Methods

The computer based training system virtX

In order to improve the teaching and training of the correct adjustment of mobile image intensifier systems the computer based training (CBT) system virtX was developed at the Peter L. Reichertz Institute for Medical Informatics in cooperation with the Georg-August-University Goettingen and the University of Applied Sciences and Arts, Hannover. This CBT system (see figure 1) offers exercise based training of the correct positioning of the C-arm for routine adjustments. A trainee can move three-dimensional virtual representatives of the C-arm, the patient and the operation table in a virtual operation theatre by using mouse and keyboard or by moving a tracked real C-arm and patient manikin which control their virtual pendants. During an exercise the trainee can generate a digitally reconstructed radiograph (DRR) at any time based on real CT-datasets and gets feedback via a traffic light, if the correct positioning is achieved. For detailed description of the system see [4-7]. Different prototypical versions of scattered radiation simulation and visualization have already been integrated in the virtX system and described and evaluated in [7] and [8]. The new simulation and visualization approach described in this paper uses the results of [8] as a foundation.

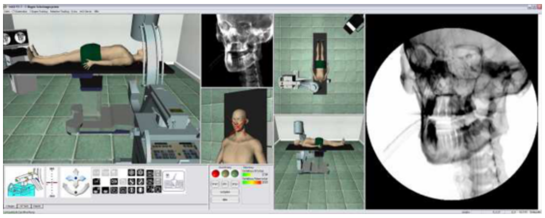

Figure 1 – Graphical user interface of the computer based training system virtX

Simulating scattered radiation using GEANT4

To calculate the physically correct behavior of radiation Monte Carlo simulation methods are a widely used and accepted procedure [9]. For the new approach of scattered radiation simulation which was integrated in the virtX training system we used the GEANT4 (*Geometry And Tracking*) toolkit in the version 4.9.3 Beta 1 [10] which uses such Monte Carlo methods to simulate the passage of particles through matter. This toolkit which uses the *Class Library for High Energy Physics* (CLHEP) is written in C++ and was developed at the European Organization for Nuclear Research (CERN). With GEANT4 a virtual environment can be constructed in which the physical interactions between a specific number of particles or photons with different objects are simulated. The user can create these objects using different geometries in the GEANT4 simulation world and specify their material properties and electromagnetic fields. For these geometries sensitive detector areas can be defined, which protocol every hit of a photon or particle. Furthermore it is possible to create primary generators in the simulation world, which emit a specific number of primary particles or photons with a discrete energy and moving direction. During one run GEANT4 simulates for every primary its way through the simulation setup until it is absorbed or it has left the simulation world.

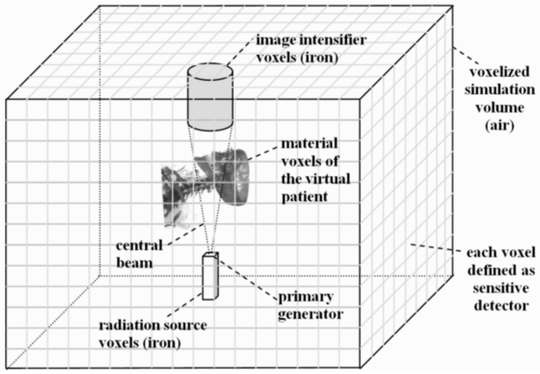

Figure 2 – Schematic description of the simulation setup in GEANT4

Similar to [8] the GEANT4 Toolkit was ported into the Visual Studio 2009 IDE so it could be integrated in the virtX project. In contrast to the simulation setup described in [8] the new approach uses a complete voxelization of the simulation environment. The simulation world, which was set to the size of 3m x 3m x 3m, was divided into 27 million voxels (300 x 300 x 300) of equal size. Each voxel was defined as a sensitive detector which protocols, depending on the simulation settings, either the energy deposit (respectively dose) in this voxel or the photons with their energies that are entering the voxel. During the initialization phase of the simulation first of all each voxel is set to the material *air* to briefly represent the operation theatre. Subsequently voxels for the C-arm are set to material *iron* depending on the geometrical properties of the simulated image intensifier (e.g. tube-image intensifier distance, image intensifier diameter).

For every simulation step the materials of the virtual patient are integrated in the corresponding voxels in the simulation setup depending on how the C-arm and the primary beam are adjusted over the patient. This is done by using the CT-datasets from the virtX system which are utilized to generate the DRR (comp. [4] and [7]). These datasets contain scaled Hounsfield values and are matched to the 3D patient model. To get the different materials for the patient-voxels in the simulation these scaled Hounsfield values are mapped to different types of tissue and their material compositions. Afterwards the indices of the voxels (where the material values have to be set) are calculated using the rotation and location differences between the primary beam and the movable CT-datasets of the virtual patient. Similar to the simulation setup described in [8] a primary photon generator was defined next to the voxels, which represents the radiation source of the C-arm. This primary generator produces a user defined number of gamma photons with an energy which could be adjusted by the tube voltage parameter in the virtX training system. The moving direction of these photons is set randomly in the area of the central beam of the C-arm, which is defined by the tube-image intensifier distance and the image intensifier diameter. The schematic simulation setup is depicted in Figure 2.

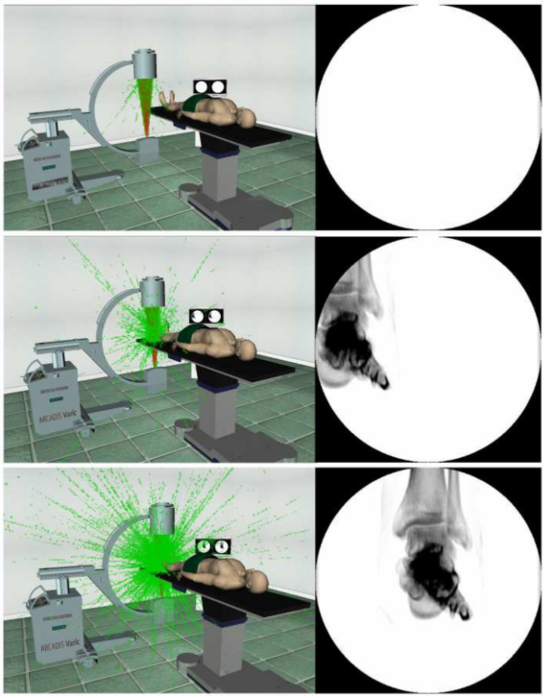

Figure 3 – Visualization of the scattered radiation simulation results in virtX

To visualize the simulation results of the GEANT4 toolkit a volume with the same voxel count and dimension as the simulation volume was integrated in the existing virtual operation theatre of the virtX CBT-system. This volume was coupled with the movement of the virtual C-arm and each voxel was set in correspondence with the sensitive detector voxel of the simulation volume. A transfer function was implemented which maps the resulting values (for example energy deposit or photon flux of the voxel) to semitransparent color values. In this way the color of every voxel in the visualization volume depicts the simulation values. In the current visualization version the colors green, orange and red are used to illustrate low, medium and high resulting energy deposit respectively photon flux for a voxel. The threshold values for the mapping of the calculated values to the colors can be adjusted over a graphical user interface in virtX. Figure 3 depicts the scattered radiation visualization results for three different C-arm adjustments over an ankle joint with the DRR and the corresponding photon flux for a tube voltage of 80kV. In these examples 5000 photons were simulated and the values represent the sum of the energy of passing photons (threshold values: green 0.1 MeV, orange 1 MeV, red 10 MeV).

Table 1 – Calculation times for the scattered radiation simulation for different numbers of simulated photons and irradiated materials

number of photons	Calculation time in seconds		
	only air	half ankle joint irradiated	full ankle joint irradiated
1000	6.1	9.9	11.4
2500	10.7	17.7	22.6
5000	17.8	30.8	41.6
10000	32.8	57.3	80.7
15000	47.2	85.8	116.7
20000	60.4	113.7	157.3

Results

Comparing the simulation results with isodose curves, which were measured during the operation of a real mobile image intensifier system, the presented simulation and visualization method represents the same information in a more interactive and spatial way for the teaching purposes during courses on radiation protection. A problem calculating physically correct behavior of scattered radiation for varying setups using Monte Carlo simulation methods is calculation time. The approach described in [8] already showed that it is possible to simulate and visualize the propagation of scattered radiation in an acceptable time for the mentioned training purposes with a certain abstraction layer. The new approach presented in this paper decreases this abstraction by integrating density values of a real CT-dataset into the simulation, cutting the simulation volume into voxels and visualizing the simulated results on every point in the virtual operation theatre. This offers a more realistic simulation and a more intuitive visualization than the previous approach. But this improvement increases the calculation time for every simulation step. In table 1 the calculation time for different numbers of photons and irradiated areas is listed (calculated on a standard PC: Intel Core2 Quad Q9000 CPU at 2.00GHz, 3GB RAM, Nvidia GeForce 9800M GS). Caused by the simulation algorithm of GEANT4 the calculation time gets bigger the more different materials are irradiated respectively gets smaller the more similar materials are irradiated. So the resulting calculation time only seems to be appropriate for a use during teaching courses for a small number of photons.

Discussion

Summarizing the aspects of this new simulation and visualization concept integrated in the virtX CBT-system one can say that it is possible to demonstrate the behavior of scattered radiation for different C-arm adjustments and irradiated materials in a virtual environment. However a faster calculation time and a more intuitive visualization (like isodose or risk curves) would be preferable. Currently the calculation for the simulation is done sequential. A speedup of the simulation by using multithreading or General-Purpose Computation on Graphics Hardware (GPGPU) methods for example with the CUDA architecture and programming API [11] has to be analyzed in future work. Furthermore not all objects in the operation theatre are currently taken into account for simulation. It would be preferable to simulate the effects on the scattered radiation behavior when using different types of operation tables, different positioning of surgical or anesthetic equipment or the different position of the surgeon and the ORP.

It would also be helpful for teaching and training during the radiation protection courses, if the virtual operation theatre in the virtX system contains movable avatars of the surgeon and ORP, which measure and visualize their individual body part radiation exposure. Through this trainees could test different C-arm adjustments and personal locations and instantly get a feedback over the specific radiation exposures and areas with high radiation risks. Also a correct modeling of the radiation source for better simulating radiation leakage or the X-ray spectrum of the central beam and an integration of the aperture functionalities of the mobile image intensifier in the simulation setup would additionally increase the level of realism of the whole scattered radiation simulation. Further research has to be done to evaluate the learning effect of this new teaching tool and to improve the level of realism and physically correctness at an acceptable amount of calculation time.

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