3D Global Estimation and Augmented Reality Visualization of Intra-operative X-ray Dose

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Abstract. The growing use of image-guided minimally-invasive surgical procedures is confronting clinicians and surgical staff with new radiation exposure risks from X-ray imaging devices. The accurate estimation of intra-operative radiation exposure can increase staff awareness of radiation exposure risks and enable the implementation of well-adapted safety measures. The current surgical practice of wearing a single dosimeter at chest level to measure radiation exposure does not provide a sufficiently accurate estimation of radiation absorption throughout the body. In this paper, we propose an approach that combines data from wireless dosimeters with the simulation of radiation propagation in order to provide a global radiation risk map in the area near the X-ray device. We use a multi-camera RGBD system to obtain a 3D point cloud reconstruction of the room. The positions of the table, C-arm and clinician are then used 1) to simulate the propagation of radiation in a real-world setup and 2) to overlay the resulting 3D risk-map onto the scene in an augmented reality manner. By using real-time wireless dosimeters in our system, we can both calibrate the simulation and validate its accuracy at specific locations in real-time. We demonstrate our system in an operating room equipped with a robotised X-ray imaging device and validate the radiation simulation on several X-ray acquisition setups.

Keywords: Surgical workflow analysis, hybrid surgery, radiation monitoring, augmented reality, RGBD cameras.

1 Introduction

The increasing use of intra-operative X-ray imaging in minimally invasive surgical procedures is increasing the exposure of clinical staff to radiation. Although the use of radioprotective equipment such as lead vests and aprons can minimize exposure, an accurate real-time estimation of the amount of radiation absorbed by clinicians during such procedures is important to improve OR safety, increase clinical staff awareness of radiation risk, and influence their behavior in high-radiation environments. For instance, such estimates can be used to generate warnings in cases of potential radiation overdose, allow surgeons to understand which steps of the surgery put them at greater risk of radiation exposure and enable the design of a safer OR layout. Large-scale efforts are being made to

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measure radiation exposure during surgery, understand the parameters that affect it, and devise recommendations to reduce the exposure of clinical staff. The ORAMED project [1,2] comprehensively measured the dose absorbed by operators at different body locations during several interventional procedures, and highlighted the need to increase clinicians' awareness of the behavior of scattered radiation. In [2], Monte Carlo based studies were performed for selected interventional radiology scenarios, varying X-ray tube parameters, and varying operator and protective equipment positions to understand the relationship between these factors and radiation exposure. Doses were also measured in the different body parts of anthropomorphic phantoms placed near a radiation source, and several configurations that reduce extremity and eye lens exposure were proposed.

Current practice requires surgeons to wear a single dosimeter at chest level under the lead vest to measure their dose exposure. Whereas traditional thermoluminescent dosimeters (TLDs) provide the dose accumulated over time, semiconductor dosimeters provide real-time measurements. The recent development of wireless dosimeters [3] further enables the real-time display of radiation dose absorption on a screen, and has been received with strong interest by clinicians. However, the use of a single dosimeter does not provide the complete picture of radiation exposure as it only measures exposure at a single location in the body. Indeed, the ORAMED study [1] demonstrated that radiation exposure differs at different body parts. Since it would be impractical for the staff to wear a multitude of dosimeters on a regular basis, especially on their head and arms, there exists a need to complement these devices with a global radiation awareness system. In this paper, we propose a system that generates a 3D radiation risk map, validated by real-measurements, and overlays it onto a reconstructed model of the OR.

Previous work has addressed the problem of radiation monitoring. [4] propose a method to simulate the propagation of radiation and to display the risk on a 3D mesh tracking the clinician's body. However, that study was a proof of concept that was demonstrated in a simple lab setup, using an invalid simulation that did not take into account real parameters and conditions. Furthermore, the application of body mesh tracking of clinicians in a real work environment is challenging due to the presence of numerous obstructions and is yet to be successfully demonstrated. In [5], a training tool was proposed that shows the propagation of radiation in a virtual setup. While such a system can be used to improve clinicians' understanding of radiation scattering, an intra-operative system that provides real-time feedback will permit better *in situ* awareness of radiation exposure risk among physicians and can improve overall OR safety.

Our contributions are therefore threefold: 1) we propose to *combine* the simulation with data from real-time wireless dosimeters in order to calibrate and validate the simulation *in situ*; 2) we propose to use a computer vision system based on multiple RGBD cameras in order to display the augmented reality risk map in a real OR setup thus providing intuitive awareness about the distribution of intra-operative scattered radiation; 3) we provide experimental results using a real X-ray device to demonstrate the proposed system.

2 Methods

We propose a system that combines real-time dose measurements with simulations of intra-operative radiation propagation for providing information about the behavior of scattered radiation in an augmented reality manner. A multi-camera RGBD system is used to capture real-time data and generate a 3D model of the room, which includes the configuration of the robotized C-arm and the clinicians. Then a Monte Carlo based simulation, built from the recorded layout of the room and calibrated with the dose values measured at certain points of the scene, is used to estimate the propagation of scattered radiation in the room. Wireless dosimeters placed at key locations are also used to estimate the accuracy of the simulation. Finally, visualization is provided by overlaying a color-coded radiation risk map onto a 3D point cloud representation of the scene.

2.1 System Setup

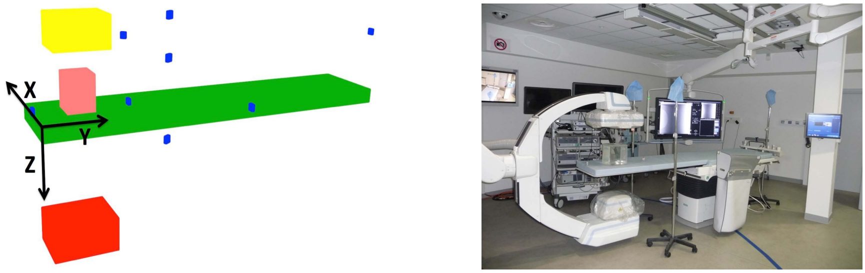
Three RGBD cameras are mounted on the ceiling of the OR using articulated arms in order to obtain images of different views of the room. These are then fused to generate a 3D point cloud representation of the scene. In the calibration step, a checkerboard is placed over the left corner of the OR table for computing the transformation of each camera frame with respect to this point. This procedure is done once per setup since the position of the motorized table can be re-obtained from the robotized C-arm.

Eight wireless Raysafe dosimeters [3] are placed at different locations in the room in order to measure the dose of scattered radiation. These sensors provide real-time dose measurements calibrated in $H_p(10)$, namely the personal dose equivalent in soft tissue at a 10 mm depth below the position where it is worn. Two of them are used for calibrating the simulation framework while the other six for providing a real-time measure of the accuracy of the simulation results. The calibration sensors are placed over the table, to the left and to the right of the isocenter of the C-arm thus receiving high scattered radiation doses, while the evaluation dosimeters are distributed in key locations of the room.

2.2 Simulation of Intra-operative Scattered Radiation

The GEANT4 [7] toolkit was used to simulate the behavior of intra-operative scattered radiation. GEANT4 applies Monte Carlo methods for simulating the passage of particles through matter by iteratively calculating the trajectories and interactions between photons and atoms from the materials present in the scene. The 3D point cloud is used to obtain the position and orientation of dosimeters and clinicians with respect to the room reference frame while the source configuration and its pose with respect to the operating table is obtained from the robotized C-arm system.

The simulation model (shown in Fig. 1a) was built by defining detector geometries having the same physical characteristics, namely shape, material and position with reference to the world reference frame, as in the real-world setup.



(a) Simulation model including radiation source (red), flat panel detector (yellow), phantom (pink), table (green) and dosimeters (blue).

(b) Experimental setup: Robotic C-arm (at 0° rotation), three RGBD cameras fixed on the ceiling and eight dosimeters placed at key locations.

Fig. 1. Simulation model and experimental setup for validating the system using an Artis Zeego [6] and its motorized operating table, a multi-camera RGBD system, RaySafe i2 dosimeters [3] and a water-filled slab phantom.

As in [5], the interventional room was represented by a volume filled with the material "air" and centered at the origin of the room reference frame obtained in 2.1. Inside, iron volumes were added to represent the image intensifier and radiation source. Their position and orientation were adapted according to the simulated C-arm configuration. In the same way, a carbon fiber parallelepiped was added for the OR table and a cubic volume filled with water and plexiglas walls for the phantom. For modeling the personal dosimeters, a 45×45×20 mm volume of ICRU [8] soft tissue equivalent material (density 1 $g.cm^{-3}$ and mass composition: 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen) was placed in the same position with respect to the radiation source as in the real-world setup. The $H_p(10)$ dose was evaluated by defining small sensitive cells of 45×45×0.5 mm inside those volumes located at 10 mm depth from the outer surface. These sensitive detectors collect information about the particle interactions that occur on the volume during a run; the total energy deposited divided by the mass, obtained from the material definition, is used to represent the personal dose equivalent. In order to compute the propagation of scattered radiation all over the room, the world volume was divided into cubic voxels forming a 3D grid. Each of these voxels was defined as a sensitive volume so that at the end of each run it is possible to obtain the accumulated dose at any given location of the room by checking the corresponding voxel. A primary generator that produces a user defined number of photons was used to model the X-ray beam. The particles' energies were sampled from simulated X-ray spectra generated for selected peak tube voltages, filtrations and Air Kerma values using the X-ray Toolbox from Siemens [9]. Their moment direction was randomly sampled inside a cone of the same diameter as the considered X-ray field of view. The physics models leading to the production of scattered radiation, namely Compton Scattering, Rayleigh Scattering and the Photoelectric Effect were also modeled.

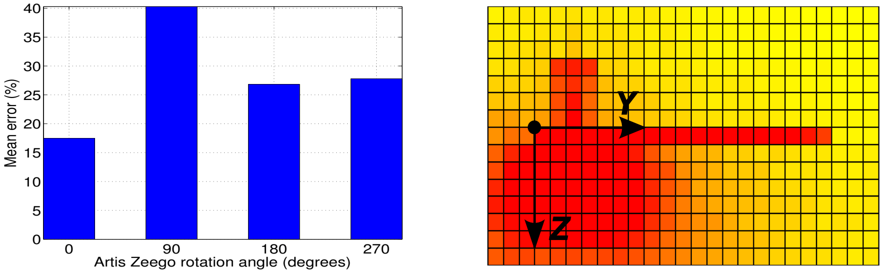
Simulations were performed for a large number of particles n. The computed doses were normalized by n, thus the number of histories only has an impact on the statistical error. A correction factor defined as the mean ratio between the measured and the simulated dose obtained from the calibration dosimeters is computed and applied to all simulation results.

2.3 Scattered Radiation Visualization

The proposed system provides three different approaches for visualizing the propagation of scattered radiation in an augmented reality manner. After a simulation run for given C-arm parameters and room layout, dose values inside every voxel element from the world volume are known. First, a color-coded radiation risk map can be overlaid onto the 3D model by coloring points according to the dose measured in the voxel that they belong to. This can help clinicians identify regions of high risk, enabling them to choose the safest position during the radiograph generation process. Second, scattered radiation isosurfaces can be generated and displayed over the model using volume rendering. This feature, besides showing the highly irradiated areas of the scene, can also be applied as an intuitive assistance tool to teach about the diffusion effects for given C-arm configurations. Third, by tracking the positions of the clinicians in the 3D point cloud, color-coded dose values in different parts of their bodies can be shown according to the simulated measures obtained in the corresponding voxels. This provides a complete picture of radiation exposure in the whole body thus complementing the information from the usual dosimeter worn at chest-level. The proposed global radiation awareness system is thereby able to make visible what is not perceived by any human sense.

3 Experiments

The system was validated with a set of experiments performed in a real operating room using an Artis Zeego X-ray robotized imaging device [6] and using the setup described in section 2.1. A 20×20×24 cm slab phantom with 10 mm thick plexiglas walls filled with water was placed over the operating table in the center of the primary beam in order to model the patient and generate scattered radiation during the imaging process. The two calibration dosimeters were placed over the bed at a distance of 30 cm on either side of the phantom. Nobody was irradiated during our tests, instead five test dosimeters were taped on drip rods installed around the operating table for reproducing the position of clinicians during a procedure. Three dosimeters were placed at different heights on the first drip rod in order to measure the radiation a clinician would receive in legs, chest and head. Two other drip rods with dosimeters taped at chest level were added to the scene: one close to the radiation source (opposite from the first) and the other at the end of the table, next to the bed control panel hence simulating the operator's position. Furthermore, an eighth dosimeter was taped on the corner of a lead panel, installed at mid distance between the radiation source and the bed control panel. Thus for each irradiation test performed we measured $H_p(10)$ values over eight sparse locations in the operating room, which



(a) Average error per C-arm configuration over all test dosimeters and imaging protocols.

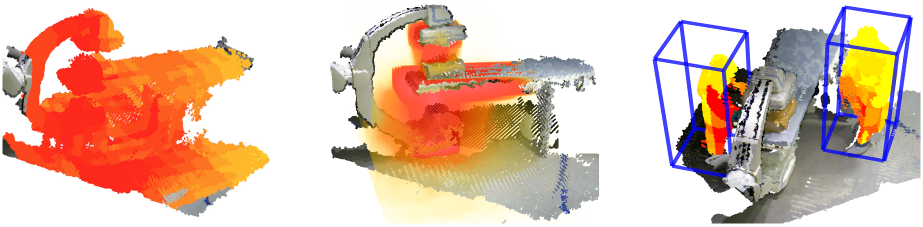
(b) Radiation map summed along the x axis, illustrating radiation backscattering.

Fig. 2. (a) Average simulation error and (b) 2D radiation risk map, where the C-arm is vertical, the source is under the phantom and red indicates higher dose.

were later used for calibrating and/or testing our system. The complete setup is shown in figure 1b. Five fluoroscopy protocols were carried out, three Digital Radiography (DS) and two Digital Subtraction Angiography (DSA) protocols, with default peak tube voltages and Air Kerma values, using the inherent 0.4 mm Al filtration proper to the Artis Zeego, for a 20-second exposure time and for four different C-arm configurations: 0°, 90°, 180° and 270° rotation. The dose values measured by each dosimeter were recorded for each of the 20 experiments.

3.1 Validation of the Simulation Framework

The positions of the C-arm, operating table, phantom and dosimeters with reference to the room frame were obtained from the 3D point cloud or from the devices and used to initialize the radiation simulation framework. Five runs with n equal to 500 million particles were performed for each tested C-arm configuration and fluoroscopy protocol parameter; the dose values measured on each sensitive cell were normalized per particle and the results were averaged over all runs. The results were compared to the dose measured by the test dosimeters after applying the correction factor obtained during the calibration of the simulation with the remaining two dosimeters. A 30% average error over all test dosimeters, all radiograph protocols and C-arm rotations was obtained. This error can be explained by the approximations made in the simulation model, in particular in the geometry and parameters, as well as in the angular limitations of the semiconductor dosimeters. While it is superior to the 10% accuracy measured in [2] using TLD dosimeters, it should be noted that the TLDs used in [2] are located 10 cm from the phantom, while we span a much larger space. Fig. 2a shows the average error for each of the four C-arm configurations. In Fig. 2b a 2D radiation risk map obtained for a C-arm in vertical position with source under the phantom (0° rotation) is provided. It is obtained by summing the 3D risk map along the x axis using the coordinate system shown in Fig. 2b. One can clearly observe the expected backscattering of the radiation under the table in this particular configuration.



(a) Color-coded radiation risk map overlaid onto the 3D point cloud of the room.

(b) Volume rendered radiation isosurface illustrating the backscattering effect in 3D.

(c) Body-part dose vizualisation: risk map shown in the clinician's bounding box.

Fig. 3. Augmented reality visualization of scattered radiation propagation by overlaying radiation risk maps over the scene's 3D point cloud representations. Red indicates higher dose.

3.2 Visualization of Scattered Radiation Results

The pre-computed dose maps are used to visualize the propagation of scattered radiation over the room's 3D point cloud reconstruction. A 3D radiation risk map is overlaid by coloring the points according to the dose estimated at their location in the simulation (Fig. 3a). Also, the radiation volume can be displayed using volume rendering to provide an intuitive visualization of 3D radiation propagation and risk isosurfaces (Fig. 3b). The clinician's 3D position is tracked by applying a background subtraction approach on the depth maps. Body-part dose can thus be shown by displaying the risk map inside the clinicians' bounding boxes only, as illustrated in Fig. 3c.

The images of Fig. 3 demonstrate how our radiation simulation and augmented reality framework can be useful to visualize the 3D propagation of scattered radiation for safety purposes. Such information is particularly useful because the radiation field depends on multiple and simultaneously interacting parameters. This field can change drastically when the OR configuration is modified.

4 Discussion and Conclusion

In this paper, we have proposed a system for visualizing the propagation of scattered radiation during intra-operative X-ray procedures. By combining the simulation with data obtained from a multi-RGBD camera system, we are able to show the radiation exposure risk intuitively by overlaying the risk map onto a point cloud, either to show the exposure of the entire room or solely of the tracked clinician. The strength of the proposed system is the combination of the simulation with data from wireless real-time dosimeters, not only to calibrate the simulation, but also to validate its accuracy online so as to provide confidence in the presented risk map. Currently, our system is not real-time because of the long computational time required for the simulation and also because the positions of the robotic C-arm and table are read manually on the devices. The system can however be used in a real-environment for augmented reality training using pre-computed risk maps validated for standard configurations. Moreover, rendering the system into a real-time one is feasible by parallelising the simulations on multiple GPUs to obtain quasi-real time computations and by obtaining the programming interface of the X-ray imaging system. Although this was not within the scope of this paper, it will be considered in future work. We also plan to include the tracking and modeling of radio protection equipment to provide online safety warnings. Another interesting but challenging extension of this system would be to use a body part tracking system in the OR instead of the clinician box tracking that we currently use: this would allow us to compute the accumulation of radiation doses per body part over time, providing very useful information in the long term to clinicians and radio protection officers.

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