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ARTICLE

Application of hand phantoms in simulations to determine the radiation exposure of medical staff

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Concerning ionizing radiation, medical workers are the largest group of exposed workers worldwide. The handling of high-energy beta emitters and the CT fluoroscopy are among the highest exposure scenarios for medical staff. With the growing use of nuclear medicine therapies and interventional procedures using real-time image control by means of fluoroscopy combined with a computed tomography (CT), detailed research concerning the radiation protection for the personnel working in these fields becomes more and more important. In this work we focus on CT fluoroscopy. To investigate exposures in detail two feasibility studies using hand phantoms are presented. The codes MCNPX and GMctdospp are employed. A comparison with thermoluminescence detector measurements is given.

Keywords: radiation protection; hand phantom; CT fluoroscopy; MCNPX; GMctdospp; dose distribution; thermoluminescence detectors

1. Introduction

The increased use of nuclear medicine therapies and interventional procedures results in larger doses for patients and medical staff. In this work, we report on staff dosimetry with focus on CT fluoroscopy. Applications of hand phantoms to measure and to model handling scenarios are presented.

2. Materials and Methods

Two measurements with a hand phantom were performed. For a first investigation, at the hospital in Coimbra, Portugal, a Philips® Brilliance 16-slice CT scanner was employed [1,2]. Thereafter, a Siemens Somatom Sensation 16 [3] was used at the Klinikum Karlsruhe in Germany (see **Figure 1** for the Karlsruhe experiment).

The hand phantom for measurements (see Figure 1) was provided by the Landesanstalt für Personendosimetrie und Strahlenschutzausbildung (LPS) Berlin. It consists of tissue equivalent materials and bones.

Thermoluminescence detectors (TLDs) wrapped in blue plastic bags were employed to measure the skin dose $H_P(0.07)$. "Photon-TLDs" of type MTS-N [4] were calibrated according to the CT device's tube voltage of 120 kV, to N-120 of the ISO narrow-spectrum series.

Figure 1. Experimental set-up at the Klinikum Karlsruhe. The hand phantom is placed in the CT device. TLDs in blue plastic bags are fixed with white tape on the hand phantom.

Two different Monte Carlo Codes were used for simulations. MCNPX (Monte Carlo N–Particle eXtended) [5] is a general-purpose code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport as well as for light and heavy ions. Hand and anthropomorphic phantoms are included in MCNPX as voxel models [1]. The voxelization was performed by segmenting different organs or tissues on the basis of CT scan images. TLD models on the hand phantom were inserted into the simulation scenario according to photos of the experimental set-up (as e.g. Figure 1).

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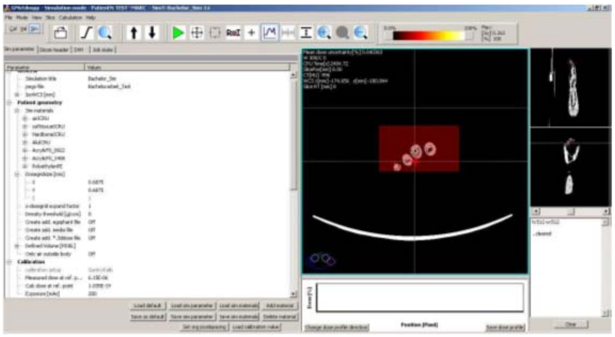

Figure 2. Screenshot of the GMctdospp GUI with a DICOM image of the hand phantom.

The software GMctdospp [6,7], developed at IMPS (in Giessen, Germany), is based on the Monte Carlo simulation package EGSnrc [8]. GMctdospp is designed for organ and effective dose calculations of CT examinations. It is a frontend of the EGSnrc user code ctdospp and includes a graphical user interface (GUI) for setup, control and analysis of simulations. It allows to process CT data sets in DICOM format.

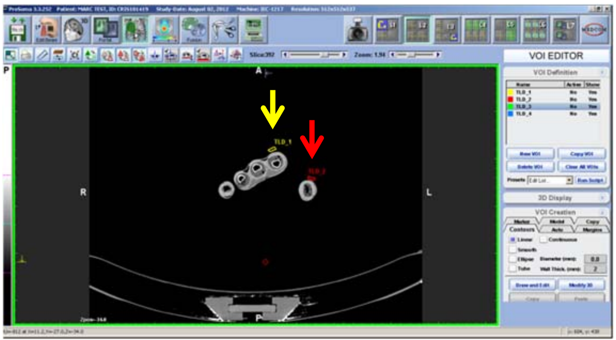

Figure 3. Arrows indicate the placement of two TLD models in the DICOM file of the hand phantom.

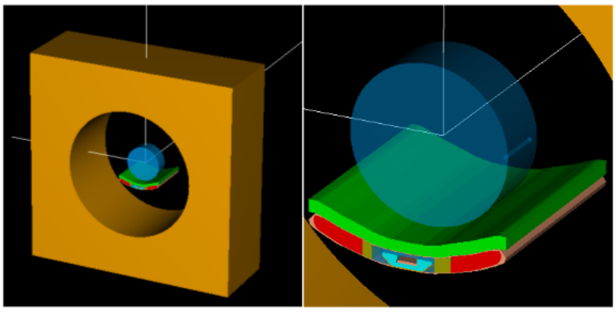

Figure 4. Model of the CT scanner as given by GMctdospp. Left: Gantry, patient table and CTDI body phantom, right: image magnification.

For the simulations, CT units (Hounsfield) are converted to mass densities and materials. DICOM data of the hand phantom were processed to simulate the dose analogue to the experiment. **Figure 2** shows a screenshot of the GMctdospp GUI. To define virtual TLDs in DICOM files of the hand phantom, the simulation software ProSoma® [9] was used (**Figure 3**) in addition to GMctdospp. **Figure 4** shows the geometry of the CT scanner used for the simulations.

An overview over different aspects of the two codes employed in this work is given in **Table 1**. Basic information about the codes as well as their specifics to simulate a CT scanner are listed. This can serve as a first guideline for potential users.

Table 1. Some aspects of MCNPX compared to GMctdospp for the present application.

MCNPX	GMctdospp
MCNPX frequently used code developed at Los Alamos National Laboratory	GMctdospp developed in-house at IMPS Giessen (based on EGSnrc)
ASCII based input files containing command lines (cards)	GUI based input and program control
Laborious procedure to create voxel phantoms from DICOM-Files	DICOM-Files directly accepted in DICOM-RTSTRUCT format
Rotational movement simulated by 36 source positions	Rotation mode of EGSnrc used
Determination of TLD position and orientation needed for MCNPX input[a]	Extra program needed to define a TLD volume in the DICOM-File

3. Results and discussion

3.1. Validation of CT scanner simulation models

Measurements were performed in Coimbra and Karlsruhe with pencil ionization chambers in CTDI body phantoms at different field positions to obtain information on the radiation field of the CT devices and to have a simple example to verify the simulation models. Note that the accuracy of the models depends on the details available for the CT scanners, such as the geometry of the bowtie filters, which affects in turn the modeled X-ray spectrum and field distribution. Not all CT scanner specifications were available from the manufacturer, as e.g. exact filter shape and thickness. Missing information was determined experimentally or estimated. Iterative improvements of the models yield a CTDI simulation and measurement agreement of better than about 10% (GMctdospp) and 7% (MCNPX).

3.2. MCNPX

Table 2. Comparison of measured and simulated dose values at the fingertips (mSv).

	Thumb	Index	Middle	Ring	Small
Measured	18.10	0.40	0.40	0.49	0.74
Simulated	14.48	0.52	0.46	0.60	0.92

The results of the TLD measurements in Coimbra (120 kV, 100 mAs, 1 s exposure time for a 360° rotation,

[a] In-house developed software (KIT) is used to match the virtual TLD arrangement according to photos of the experiment.

and body bowtie filter) and simulation agree within 50% or better (for details see [1]). Exemplary dose values are given in **Table 2**. This is a good agreement having in mind that uncertainties in such measurements may contribute with more than 50% [10]. Representatively, two simulation results are shown in **Figure 5**. The dose varies between 0.06 mSv (minimum) close to the elbow and 14.48 mSv (maximum) at the tip of the thumb. Figure 5 illustrates the accuracy of TLD positions as source of uncertainty. Only 2 mm displacement of the beam focus at the tip of the thumb (indicated by the arrows in Figure 5) changes the dose by a factor 10 from 1.27 to 14.48 mSv. Thus the position accuracy is of main importance.

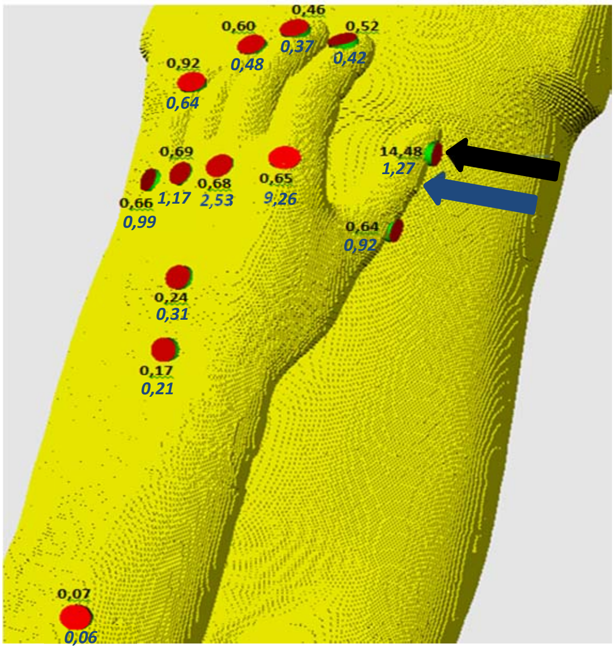

Figure 5. Simulation results at different TLD positions of the hand phantom. The hand is placed on an anthropomorphic phantom as in the experiment at the hospital in Coimbra. Arrows indicate the two different beam positions and the corresponding colored numbers the adjacent TLD dose in mSv.

3.3. GMctdospp

DICOM pictures of the hand phantom placed in the beam of the CT scanner (Figure 1) together with the TLD positions are shown in **Figure 6**.

For the CT device (settings 120 kV, 200 mAs, 1 s exposure time for a full 360° rotation, and head bowtie filter) the corresponding dose together with simulations results are given in **Figure 7**.

The doses vary from below 1 µSv (farther away from the beam) up to maximum 28.5 mSv (measured) or 54 mSv (simulated) at the beam focus on the outer side of the small finger's tip (position No. 6 in Figure 6). The simulated dose decreases for the latter position to 14 mSv when a shift of the beam focus by 2 mm is performed. This confirms, again, the strong dependence of the TLD position accuracy. As a result, within the given uncertainties, the simulations reproduce the measurements and are applicable to perform CT investigations in the described scenarios.

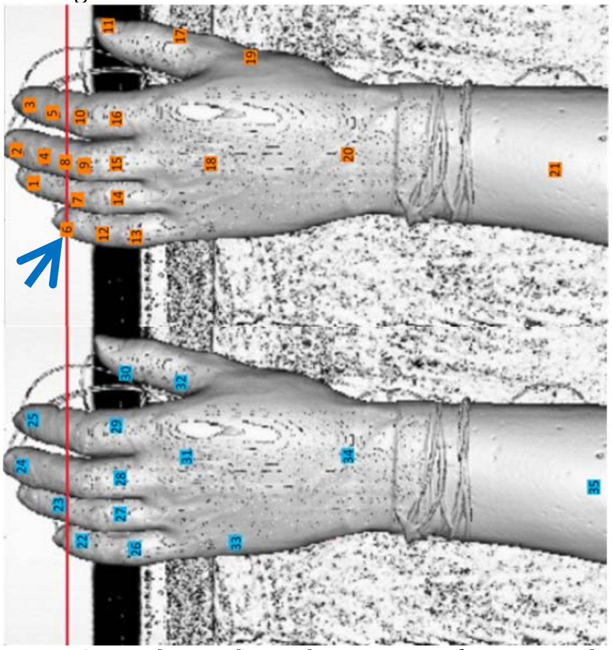

Figure 6. Numbers indicate the positions of TLDs on the outside (at the top) and inside (at the bottom) of the hand phantom. The red line indicates the X-ray beam focus. The arrow points to number 6, the position with the highest exposure.

4. Conclusions and outlook

The codes MCNPX and GMctdospp are both qualified for CT fluoroscopy simulations. Comparable results were obtained. The range of maximum dose, determined by the measured and simulated values, was at the Philips CT scanner 14.5 to 18.1 mSv and at the Siemens device 28.5 to 54.1 mSv. This reflects the factor of two for the different beam currents.

In the given scenario, the annual skin dose limit would be exceeded within 10 to 35 identical irradiations. This result confirms that CT fluoroscopy is among the highest exposure scenarios for medical staff.

To conclude the present work, Monte Carlo codes are a useful tool to investigate the complex radiation field for scenarios in CT fluoroscopy. In particular for inhomogeneous radiation fields, where measurements could be difficult, time consuming or not feasible at all, simulations are advantageous. Different scenarios can be simulated and situations with highest exposures can be identified. The fluoroscopy project is part of a EURADOS working group [11] and will be pursued on a European level.

For future investigations concerning CT fluoroscopy it is planned to apply methods recently investigated at KIT [12], to include hand movements in the radiation field. Handling scenarios are recorded thereby with a four camera system to obtain 3D information which allows a geometrical modeling of the relevant objects, e.g. the hand. A subsequent implementation into

MCNPX allows simulating sequences of action.

Moreover a new generation of gamma camera is being developed in the BOOSTER project [13]. A hand held configuration will provide an imaging technique to locate gamma-ray emitting sources. Associated with the above mentioned 3D information, this would allow to include measured source information with the aim to improve spatiotemporal modeling of handling scenarios.

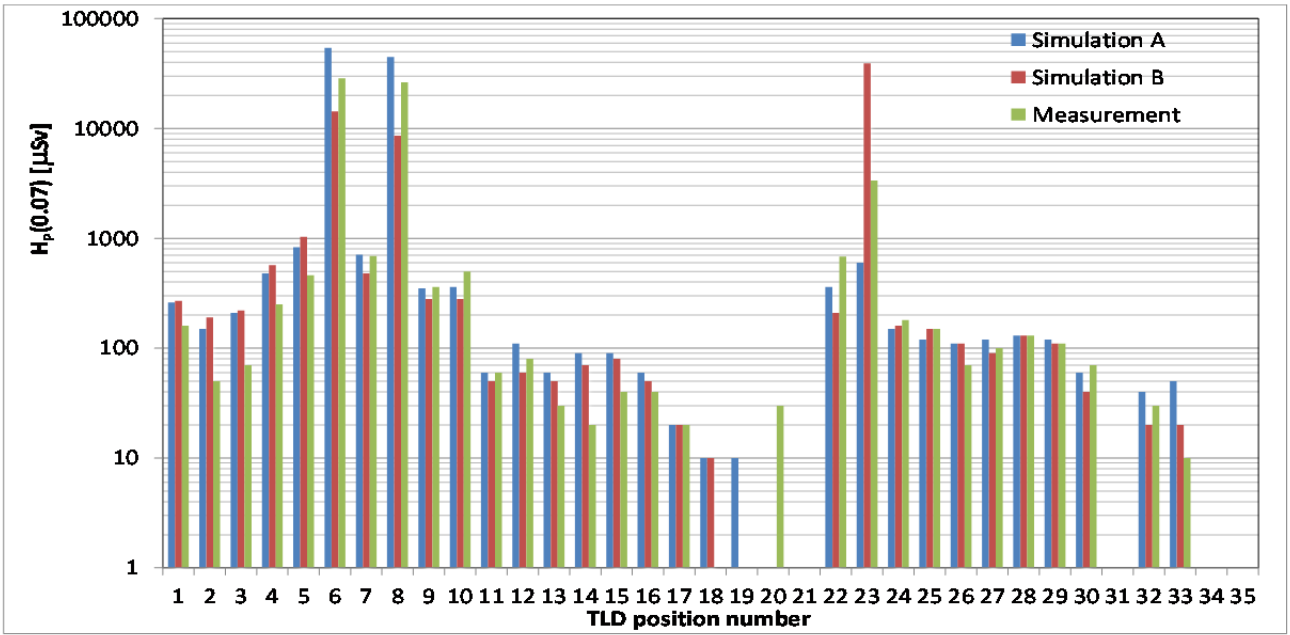

Figure 7. Simulated and measured dose distribution on the hand phantom at the different TLD positions. The difference between “Simulation A” and “Simulation B” shows the effect of a 2 mm offset from the X-ray beam focus. Doses below 1 µSv are not shown.

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