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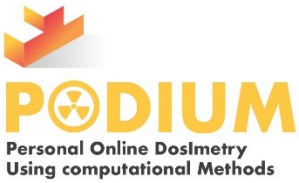

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D9.110 - Report with a documented test of concept in an experimental set-up*

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*Validation of the application in a controlled experiment set-up in a hospital

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Abstract

The objective of the PODIUM project is to develop a user-friendly online tool to calculate the radiation dose to workers. This will be done by combining positioning information from individual staff members using the developed IPS based on the Kinect 3D camera as well as information on the radiation field and the geometry of the room.

The main aim of the Work Package 4 is to validate the tool in hospitals, in particular in interventional radiology. In order to accomplish this, the work was divided into two main tasks. The first task is to test the online application in an experimental set-up using clinical X-ray equipment and the second was to test the tool during routine or typical clinical interventions.

The goal of this report is to present the work that has been done on the first task, validation in an experimental set-up.

I. Introduction

The overall purpose of the project: The goal of this project is to develop a software tool - an online system – that will calculate the radiation doses to workers by combining the positioning information for staff and possible objects such as radiation protection screens (constituting the indoor positioning system, IPS) with information on the field of scattered radiation and the room geometry. The project work package (WP) 4 is focused on validating the tool for use in hospitals, especially in interventional radiology and cardiology, where the highest doses to staff in medicine can occur. Hospital staff that are classified as radiation workers are normally equipped with small personal radiation dosimeters. Such point dose measurements might not be representative for the whole body due to in homogeneities in the radiation field. Therefore, in some specific cases the radiation workers are requested to wear additional dosimeters at the hands or close to the eye lens – this can prove to be practically difficult and compliance with wearing dosimeters is an issue. For interventional radiology it could be anticipated that the online system would improve the knowledge of radiation dose to staff, not only the whole-body dose, but also the radiation dose for the lens of the eye and the hands.

Clinical demands and challenges: The on-line system – both hardware and software – must meet the demands of the hospital environment, the dose values have to be reasonably accurate and the system feasible to use in the hospitals. This includes e.g. safety issues when introducing technical devices into operating rooms (some interventional rooms are classified as operating theatres) and practical issues concerning handling of the tool by the hospital staff. There are also several other challenges. Privacy and ethical concerns are highly relevant in this scenario with a camera monitoring movement in the room. The operating rooms are different in size and the equipment differs in types and usage. The operating team ranges from two persons to in some cases more than ten, working at different positions around the patient table. The prerequisites for using radiation protection techniques– e.g. ceiling or table mounted shielding – or staff moving out of the room during image acquisition, differ between rooms and procedures. Thus, the calculations are challenged by the varying usage and it could be anticipated that a simplified version of the simulation/calculations such as using pre-calculated look-up tables with dose-conversion coefficients has advantages. However, simulation of each irradiation event in real-time and on demand could be desirable. The validation of the on-line system from taking into account these different factors is very much needed.

This report concerns the first task 4.1 of WP4: The validation of the application in a controlled experimental set-up in a hospital.

The milestones related to this task are:

MI 1.1: Indoor position system - ready: M12
MI 1.2: Geometry and radiation field mapping algorithms - ready: M12
MI 2.1: Database of phantoms of different postures and statures - ready: M9
MI 2.2: Database with fluence to dose factors for application in WP4 and 5: M14

II. Validation strategy and plan

The strategy

This section describes the prerequisites for the calculations and the on-line system and its implications on the validation. A schematic outline of the items to explore is presented in Figure 1. The specific items are further described below.

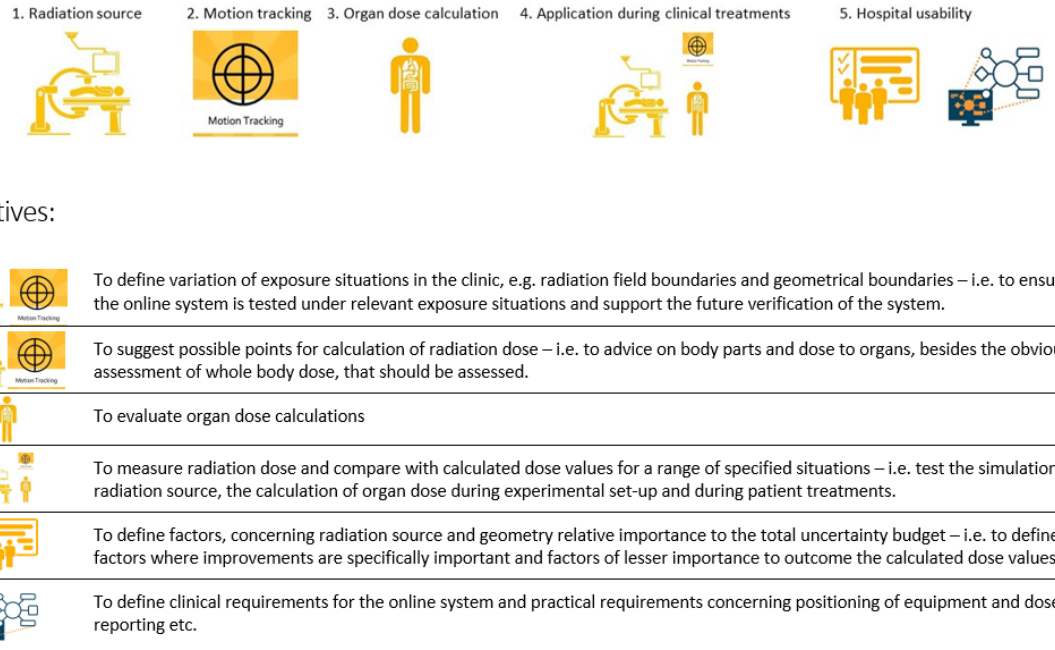


Figure 1. Schematic outline of the different items to be validated.

Radiation source– scattered radiation

The scattered radiation around the patient needs to be calculated based on information about the radiation source, the output from the source and the irradiated volume. That is, the scattered photon energy distribution and amount of radiation depends on technical and geometrical settings of the x-ray tube and on the patient position and size. The scattered radiation level differs in the room, depending on the geometrical position (x, y, z-coordinates). This information is needed both for calculating the worker dose based on a pre-calculated conversion coefficients data base and when using accelerated Monte Carlo calculation. In the case of "on-demand" calculations, the technical values and patient related values and the position of the staff members will be needed promptly in order to calculate the angular and energy distributions at the exact position. The scattered radiation field will have to be re-calculated whenever one of these parameters has changed significantly. All required information for calculating the radiation field should be available. The validation should include the availability and correctness of the information of the above parameters and also their relative importance for the final result.

Motion tracking - staff and object monitoring and global positioning system

The monitoring system (IPS) has to register time and position of staff members and other movable objects. The IPS should be able to track and identify the staff members and possible moving objects and register their body joint positions as a function of time. The time and position of staff members and movable objects are registered in defined intervals. These registrations have to be started as soon as the procedure begins and continue until the procedure ends. Preferably this tracking or registration of positions should be performed only when the irradiation is on in order to limit the amount of data

registered as computer storage requirements are another relevant issue for some very long patient procedures.

In interventional radiology, the staff dose is also affected by the position of fixed objects, and position of possible movable objects e.g. table-side or ceiling-mounted radiation shielding. All fixed objects should be defined in the geometrical definition of the specific examination room.

The position of the operator in the radiation field has to be determined. Coordinates given by the IPS have to be related to the radiation field coordinates and to the coordinates of the irradiated body. It´s therefore important to be able to create a global coordinate system for a specific operating room. The software has to handle staff positioning and scattered radiation geometrical data combined.

Organ dose calculation

The project aims at simulating the operator using a computational phantom, that is calculating absorbed dose to organs or assess effective dose. So far, this feature has not been included in the tool, so measurements and calculations for this deliverable are presented for radiation protection quantities – especially $H_p(10)$ where no simulating the operator using phantoms including organs are needed.

The validation plan

Table 1 shows the validation plan. The tracking of the operator's movement was first tested on site in an interventional room by mimicking operator without patients involved. In the second step, the operators were simulated using dummies and their positioning was modified. In order to simulate the patient, an anthropomorphic phantom was used. The performed measurements will give useful information to improve the simulations, source specifications and geometry mapping for the clinical simulation. The validation experiments were performed using clinical X-ray equipment, where X-ray fields, field size and angles of the X-ray tube were altered to create possible values and positions from our experience of clinical treatments.

Table 1. The validation plan.

Motion tracking: Exploring position variability and demands on motion tracking.	**Experiment set-up:** Investigating positioning of the IPS and accuracy and uncertainties. Explore the tracking of the operator using test persons and phantoms.	**Dose quantity:** Dose rate in different operator positions and different parts of the body. Measurements performed using semiconductor dosemeters.
Radiation source/field and scattered radiation: Radiation field vary substantially between image acquisition for the same treatment, different treatments and different x-ray machines.	**Experiment set-up:** To validate the radiation field, homogeneity and geometrical features of the scattered field measurements will be performed. The operator is mimicked and exposures are measured for some relevant clinical realistic scenarios.	**Dose quantity:** Dose and dose rate in operator positions. Geometrical specific measurements using laser. Measurements performed using semiconductor dosemeters.
Radiation dose: Validate Hp(10) calculations with measurements.	**Experiment set-up:** Measure Hp(10), using personal dosimeters on surface using a phantom set-up	**Dose quantity:** Personal dose equivalent Hp(10)

III. Preparations and experimental site

The first task for this work package - preparing to be able to perform measurements in hospitals has been carried out. One challenge was to establish contact with managers and clinical staff to get access to equipment and make measurements in the clinic. A significant amount of work has been done to communicate with the clinical staff to establish good relationships. These tasks, which at first may be considered insignificant, are crucial for the success of the entire project. Even when performing experiments with clinical equipment and without patients the approval from the clinical team and other relevant parties in the hospital is essential. Another challenge was to receive ethical approval for the clinical studies. Ethical approval for clinical measurements has been obtained for the participating hospitals in Sweden, Ireland and Belgium.

One part of the validation experiments was performed at Skåne University Hospital in Malmö. A dedicated operating room for interventional radiology was selected. This room was equipped with a ceiling-mounted angiographic equipment (Artis Q, Siemens, Erlangen, Germany) dedicated for angiographic investigations. In the room – hereafter named 105 – interventions, in particular including treatments of the vessels in the arms and legs are performed. Full anesthesia is not employed in the room. Therefore, the size of the room is small compared with other interventional rooms in the hospital.

The indoor positioning system – Kinect2.0 – was installed together with the software developed in the project. Several positions of the IPS in room were investigated. The Figure 3 shows the chosen field-of-view.

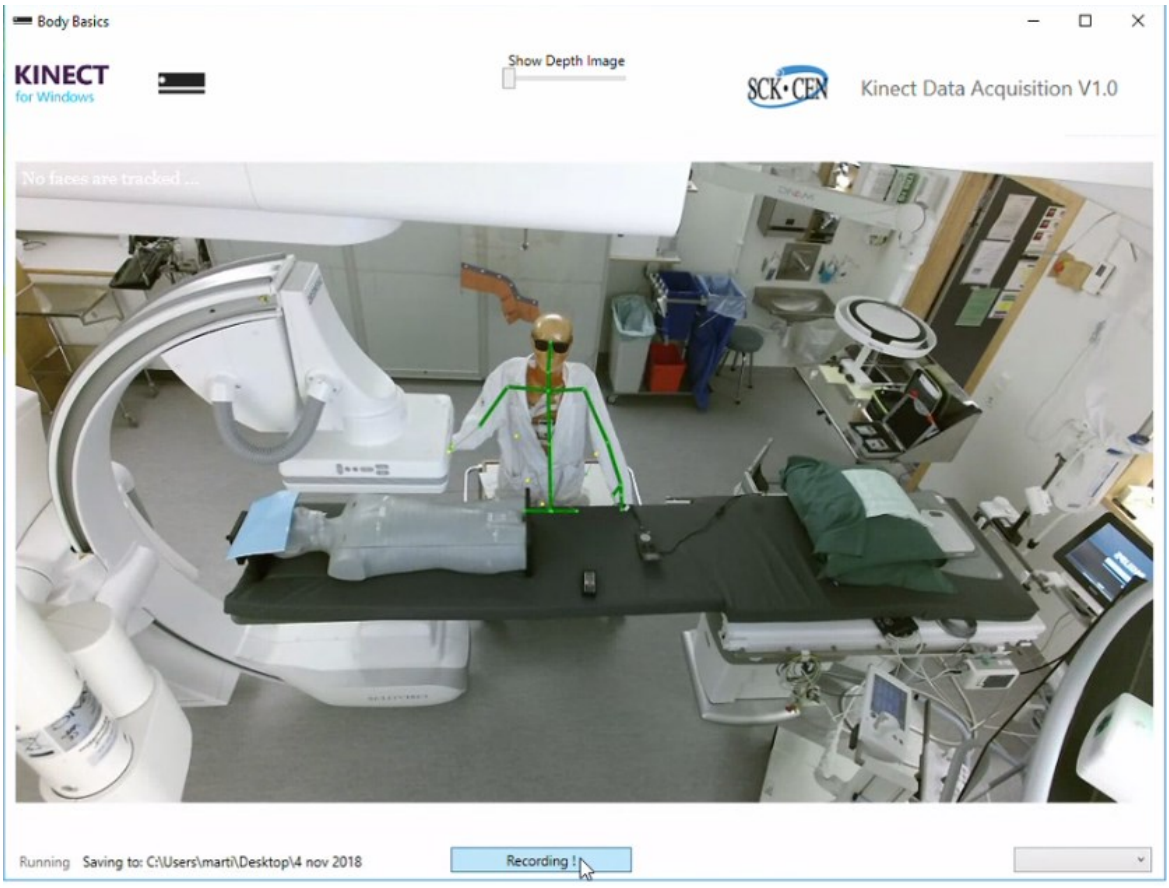


Figure 3. A recorded frame from the ceiling mounted Kinect.

The geometry was mapped in order to give input to the calculations – using the method described in D9.106 “Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application Part 1: Workplace geometry”. The result of the CAD mapping is shown in Figure 4.

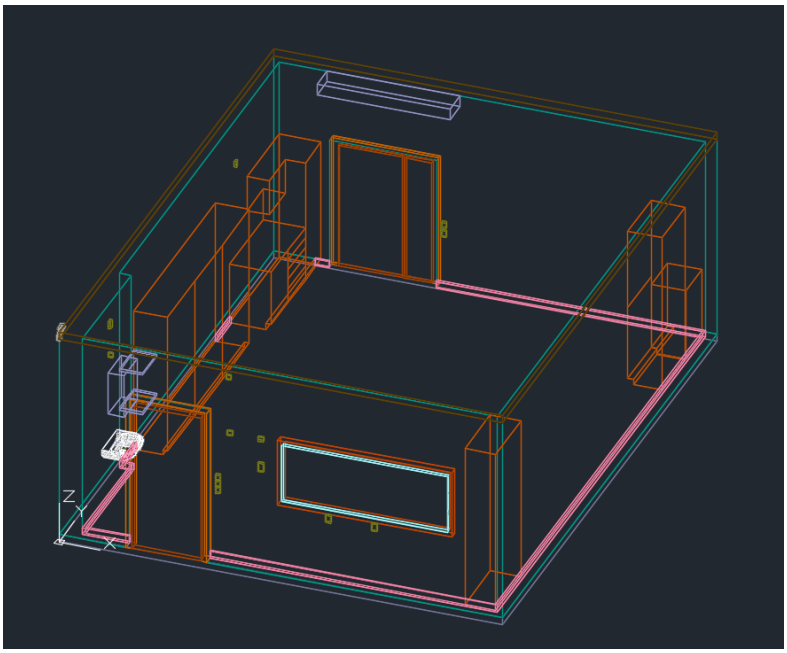


Figure 4. The CAD map of the interventional room 105 at the hospital in Malmö.

IV. Indoor positioning system IPS – functionality and accuracy

The IPS developed in work package 1 was used. The system is described in the two deliverables: D9.103: “An IPS based on an infrared reflection time-of-flight sensor camera together with the corresponding software” and D9.105: “An IPS based on a developed camera network system and the multi-image acquisition computer system with the corresponding software.”

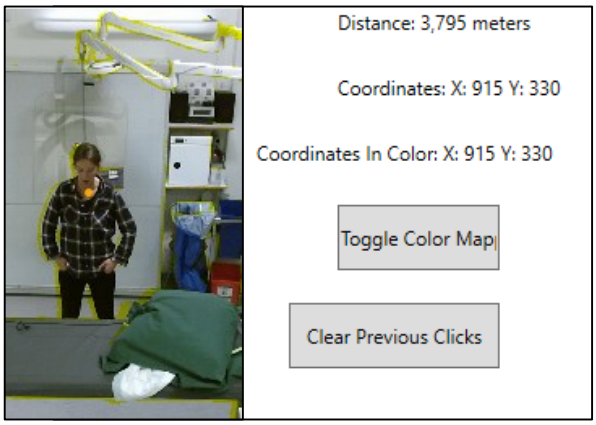
The IPS was not in full functionality for use in our first validations because it was developed during the time the experiments were performed. However, its functionality was investigated. At each investigated intervention the person of interest (the operator) was given a tracking ID when moving in and out of the room and around the patient. The delivered output data for the tracked position from several body parts was generated with an acceptable accuracy: the trunk of the operator, the head of the operator, the hands of the operator. The output database contains the tracked position of all monitoring data from the staff and object monitoring database. Each entry should contain: procedure identification, time, staff or object identification and positions of the staff or movable object joints. The virtual phantom for the simulations will be assumed to be “positioned” at these data points.

Installing the IPS and the associated software introduced several issues. The field-of-view should not be obstructed by any moving part of the x-ray equipment. For ceiling mounted x-ray equipment this could happen. Several placements were tried out the room and also in an interventional room in Belgium with a trial and error method. While in Belgium one preferred position was on the large image screens positioned in front of the operator, this position was not possible in Sweden. Both the camera view from behind and from the front was tried out in Sweden but meeting all kinds of clinical difficulties. It is not easy to determine a suitable position without a detailed knowledge of clinical practice. Using one Kinect camera for recording moving parts of the X-ray equipment will always

generate blind spots in the operating room. That is one of the reasons why in PODIUM we are also developing an IPS with two camera's. However, with knowledge on how the procedure works and how the staff operates and moves the equipment during procedures an optimal camera position can be found, also using only one camera. The optimal final position for this room - high up mounted on the ceiling - was finally determined.

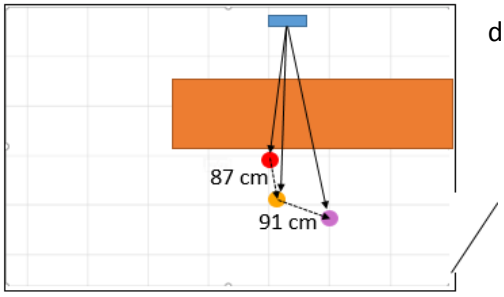
Figure 5 shows an investigation of the given distance from the Kinect to the persons. The position from the Kinect to the upper part of the body was measured using a laser measuring tool and compared with the result from the Kinect. The result from one of these tests is shown in Figure 5. The conclusion of the distance measurements is that the accuracy of the Kinect2.0 is sufficient for tracking the movements of an operator working 2-4 meters in front of the camera. More tests may be needed.

a)



b)

c)



d)

Distance upper torso to Kinect	Laser measure (m)	Kinect cal. (m)	Diff (m)
Position A	3.026	3.044	0.018
Position B	3.832	3.795	0.037
Position C	4.186	4.084	0.102

Figure 5. The figure shows a measurement test with the Kinect. a) shows the software tool giving the x and y values. b) shows the three different positions. c) shows the distances of the three cases measured with a laser rangefinder (Bosch GLM 100 C). d) shows the calculated difference between the measured distance and the Kinect**.**

The output data from the Kinect were created as a comma separated values (CSV) text file and rewritten and stored in to an Excel sheet, where each row in the sheet includes the timestamp, a phantom tracking ID and the skeleton joint positions relative to the Kinect. The timestamps of the Kinect output file have to be synchronized with the X-ray machine data, as the exposure scenario should include the operator´s position at the exposure. In the validation – as there is not yet communication between the X-ray system and the Kinect – the Kinect tracking was recorded in a standalone function and manually correlated to the exposure data.

The Monte Carlo simulations will be done at defined intervals where each simulation represents a fixed geometry valid for a short time period of the procedure. The tested IPS can track the operator at a maximum rate of 30Hz and store up to 30 positions per second. An algorithm is applied to the output

file from the Kinect Data Acquisition, so that a new file with a constant sample rate of 1Hz is produced and used for the dose calculation. Details are presented in D9.105.

The duration of procedures could vary between about 15 minutes and 4 hours in some extreme cases up to ten hours, which will create large CSV files. There is a risk that the software could crash during the rewriting from the CSV file to the Excel sheet if this file is too large compared to the RAM memory. Depending on the size of the CSV file and the amount or RAM memory on the computer operating the Kinect, this is another issue to be investigated during the clinical validation study. In the future, this issue could be solved by just storing the data when the beam is on.

For a one camera operating system with several staff members moving around in the room occlusion could be an important issue, where staff members are positioned between the operator and the Kinect, leading to an incorrect skeleton representation of the operator. The validation in the clinic will be performed on the main operator, but the Kinect will record several members of the staff so the IPS needs to determine which Kinect phantom tracking ID belongs to the main operator. The frequency and impact of this problem is dependent on the Kinect position, and of course on the number and the movement of the staff.

The problem of occlusion can not only result in incorrect skeletal representation. The Kinect can also swap the phantom tracking ID between two staff members. If this is not considered, the possibility that the main operator and another staff member responsible for the occlusion swaps tracking ID, the IPS would not simulate representative dose values. During a procedure, all staff members should preferably leave the operating room under image acquisition.

It is evident from this investigation that occlusions are a problem. The outcome of calibration was satisfactory for the simplest situations with no occlusions and the person of interest in a reasonable distance from the camera. However, if the main operator walks in and out of the kinetic view during the procedure, a system to ensure that the IPS recognizes the person that was being tracked will be needed, i.e. an additional external tracking or face recognition system. This is being developed in WP1.

Issues encountered that have to be solved.

Item 1: Setting up and calibrating the IPS

Camera positioning is crucial. A standardized optimized position has been difficult to identify, as each treatment room is unique. Therefore, careful instructions – also including practical information – must be developed if the current technical solution is used. Input from the clinic is vital and the instructions have to be combined with clinical specifications.

Item 2: The accuracy of the IPS system - geographically in the room.

The working range of the camera – including the assessment of the uncertainty - is about 5 meters. This can be a limiting factor for some clinical applications as these are performed in large operating rooms.

The way to find a unique identifier of the operator must be improved. The system must be able to consistently track a person of interest, even if occlusion occurs or the person leaves and returns to the camera's field of view. This is a small problem for standardized treatments such as cardiac treatments, where the operator and assistant staff work in a static way. However, for other types of work, the clinical team consists of several people who work more dynamically. This can be a major problem.

Item 3: Coordinating the output data from the IPS and x-ray machine with a geographical reference system.

The Kinect produces data with reference to the Kinect camera. This is not directly useful for the calculations and correlation with the geographical positioning of the scattered radiation is needed. The correlation of the Kinect position data and the data in terms of irradiation events from the x-ray machine has also to be performed. That is, the timestamps of the Kinect output file have to be synchronized with the X-ray machine time. This could be an issue and some correction may be need. During our measurements this has been performed manually but has to be automatic in a future product.

V. Scattered radiation determination and dose assessment

The scattered radiation is calculated with clinic and treatment specific data. These data have to be retrieved in real-time or at a minimum be available at the end of a procedure.

The basic data needed for simulating the x-ray spectra:

- target material
- anode angulation
- tube peak voltage
- tube filtration

The target material and anode angulation is not data that is easily available in the clinic. Tube voltage and tube filtration is altered automatically based on clinical protocols and patient thickness during the fluoroscopy and image acquisition.

The scattered radiation is also specified by:

- tube current,
- exposure time
- source to detector distance
- thickness of the exposed body
- attenuation in the couch and mattress

The first three parameters are technical parameters from the x-ray machine and give the output from the x-ray machine. The output could also be defined by the dose in the reference point or kerma-area product given by the x-ray equipment. The thickness of the exposed body could be predicted knowing the weight, length, sex and age of the patient. The attenuation in the couch is not readily available in the clinical, but can be experimentally estimated or may be available from the manufacturer.

Scattered radiation from an x-ray tube has been simulated in other studies and the methodology exists. The challenge for this application is to be able to, in real-time, simulate an inhomogeneous 3D scattered field in order to be able to assess organ dose given the varying output and exposure situation.

Extracting technical data from the x-ray machine was explored. The availability of the so called radiation dose structured report (RDSR) was explored. The RDSR from different vendors and different x-ray machines should contain the same data due to technical standards. However – vendor specific and user specific data could be included and it is needed to be able to extract data from any vendor. The work station belonging to the x-ray equipment is the most reliable source for this technical data. A complete set of data in a suitable format is hard to find elsewhere, e.g. PACS may only contain images. The images stored contain some of the data needed, however data from fluoroscopy is not stored.

Other data sources, e.g. a dose management system, could contain the data in a structured manner. However, this is highly dependent on the hospital protocols. In the example hospital the extraction was set-up differently for different x-ray machines and the data needed was therefore not readily available.

Figure 6 gives a schematic overview of data sources that could contain important data. The on-line system has to be specific about what data should be delivered and in what data format. In our model room the RDSR-files were available from the work station after each treatment. Note that the treatments data are only stored for a limited time as the memory in the work station is limited.

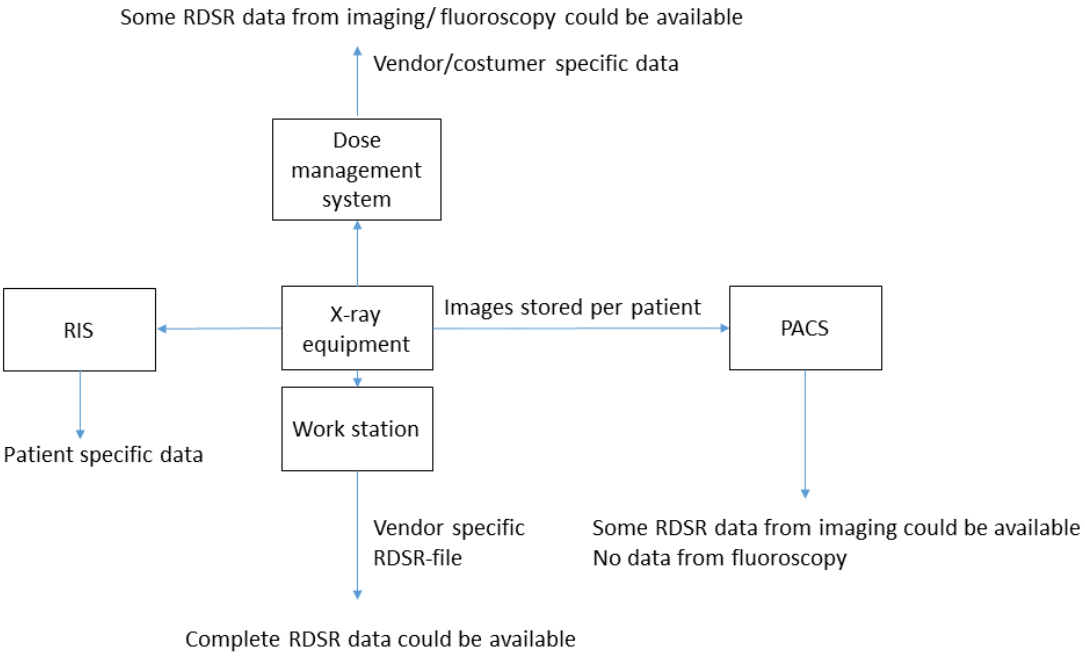


Figure 6. A schematic over view of where different machine data from a procedure are available.

Figure 7 shows the data explored and an overall judgment of the usefulness. The time stamp has to be synchronized with other equipment and programs. The position of the table in lateral and longitudinal positions may be set to zero by the operator in order to set reference for an anatomical structure during the treatment and this zero position is not standardized and is likely to vary with each room installation making it not useful as it is. The position is needed for the PODIUM approach in order to give the geographical position of the irradiated volume.

Administrative data	
DateTime Started: 2018/05/22, 12:26:12	(✓)
Device Name: ARTIS109359	✓
Device Serial Number: 109359	✓
Geometrical data	
Positioner Primary Angle: -1 deg	✓
Positioner Secondary Angle: -0.7 deg	✓
Distance Source to reference point : 635 mm	✓
Distance Source to Isocenter: 785 mm	✓
Distance Source to Detector: 1100 mm	✓
Table Lateral Position: 1024.5 mm	✗
Table Height Position: 231.8 mm	✓
Table Longitudinal Position: -15.1 mm	✗

X-ray Generator and x-ray tube	
Pulse Rate: 4 {pulse}/s	✓
Number of Pulses: 14	✓
KVP: 85 kV	✓
X-Ray Tube Current: 18.1 mA	✓
Exposure Time: 43.4 ms	✓
Pulse Width: 3.1 ms	✓
Exposure: 785 uA.s	✓
Focal Spot Size: 0.4 mm	✓
X-Ray Filter Thickness Maximum: 0.6 mm	✓
Dose values / irradiation field	
Dose (RP): 2e-005 Gy	✓
Dose Area Product: 5.6e-007 Gy.m2	✓
Collimated Field Area: 0.10877937 m2 - @ detector	✓

Figure 7. A list of available data. The green check mark indicates that the data is useful and available as is. A red cross indicates that the data is needed, but the information is not useful as is.

Data variation between treatments and patients. The variation between different patients and/or treatments types is significant. Data from room 105 was investigated. The first 4000 irradiation events from 41 treatments in room 105 in 2018 are shown in Figure 8 and 9. The variation in data for tube voltage and added filtration is significant. Other parameters such as tilting, field size and tube current also vary between irradiation events.

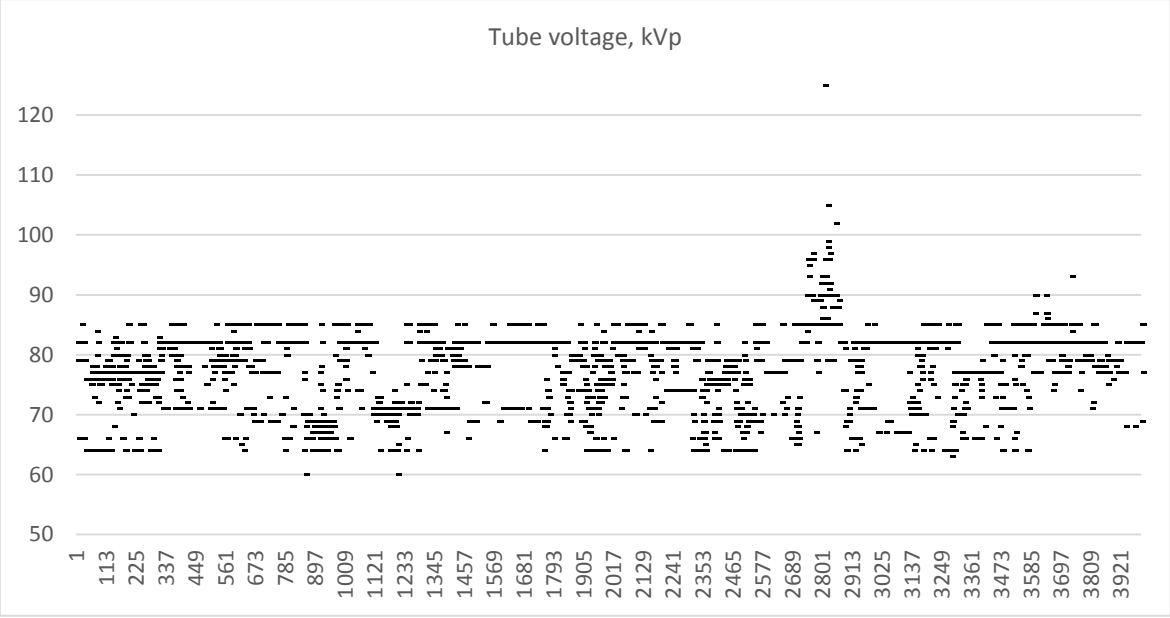


Figure 8. The different tube voltage used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö.

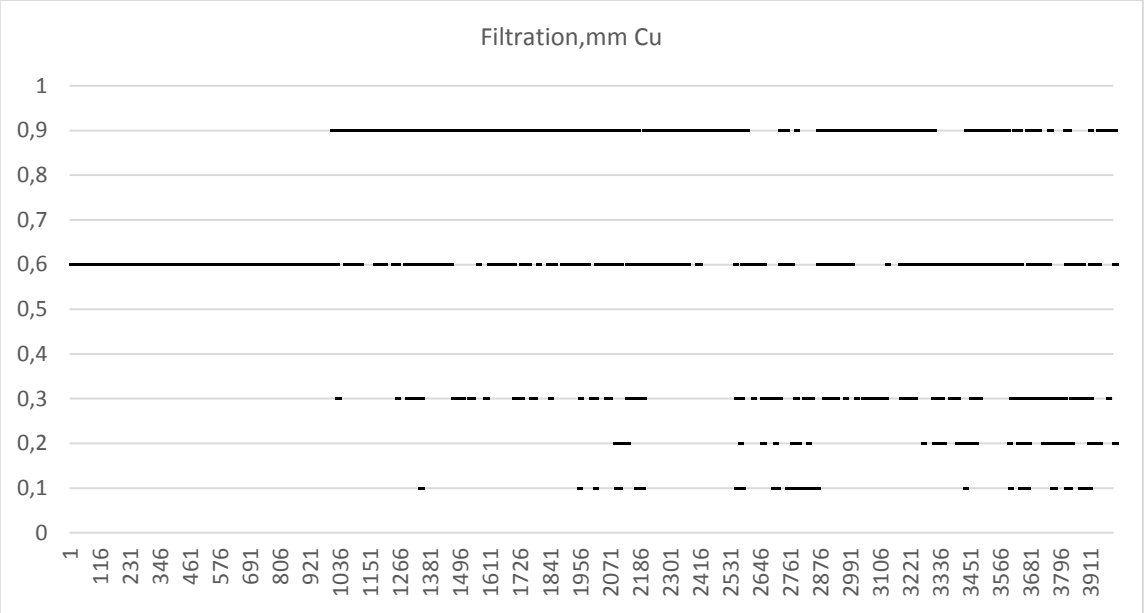


Figure 9. The different tube filtrations used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö.

Issues encountered that have to be solved.

Item 1: Specification of the data and the data format needed for calculations

In the validation, manual work was performed in order to extract data needed from the x-ray machine. It is important to be able to perform the data extraction automatically for all sorts of angiographic x-ray machines. The electronic format of the data needs to be specified.

Item 2: The position of the irradiation volume.

The specification of the position of the irradiated volume has to be solved.

VI. Workplace geometry and radiation field map

The report "D9.106: Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application" was devoted on how to characterize the workplace geometry and radiation field mapping. Some work regarding the radiation field mapping is still on-going and this has to some extent influenced the validation work.

Work place geometry has been mapped out for the room 105 used for the validation. The Structure sensor (Occipital Inc.) was used. This device is a 3D camera attached on an iPad. Structure sensor 3D camera created a 3D mesh environment by walking around and record different views of the operating room using the "Canvas" app in the iPad. After the generated 3D mesh was created the mesh file was send for post-processed, which is a featured app service called "Scan To CAD". The generated 3D mesh by the Canvas app and the post-process CAD file of the operating room number 105 at the Malmö Hospital are presented in Figure 10. The significance of mapping out the rooms in detail needs to be investigated.

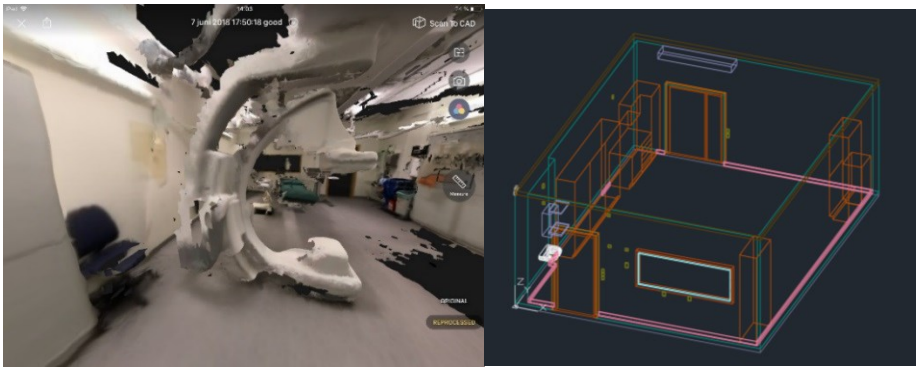


Figure 10. Left, a print screen of the generated 3D mesh of the operating room using Structure sensors and the app Canvas. Right, the post-processing CAD file of the operating room using the "Scan To CAD" service and shown in the computer software AutoCAD.

Each part sending data to the IPS has an individual reference system. The tracking position of the main operator will be relative to the Kinect. The machine parameter for the X-ray tube will be relative to the machines center of rotation (which is the same as the isocenter of the machine) and the machine bed positions are given relative to a specific position on the bed. However, the Monte Carlo Simulations will only use one reference system. One solution would be to include the coordinate system of the operating room as a third coordinate system and determine the Kinect and the machine reference points in the room coordinate system. A problem with the X-ray machine coordinate system is that the whole X-ray machine is movable, so the fixed center of rotation will be the same relative to the X-ray tube but the tube itself moves around in the operating room. The different reference systems are shown in Figure 11. One solution would be to relate all coordinate system to the isocenter and update all coordinate system, once the isocenter changes position in the room. The solution for this issue is further being developed in WP1.

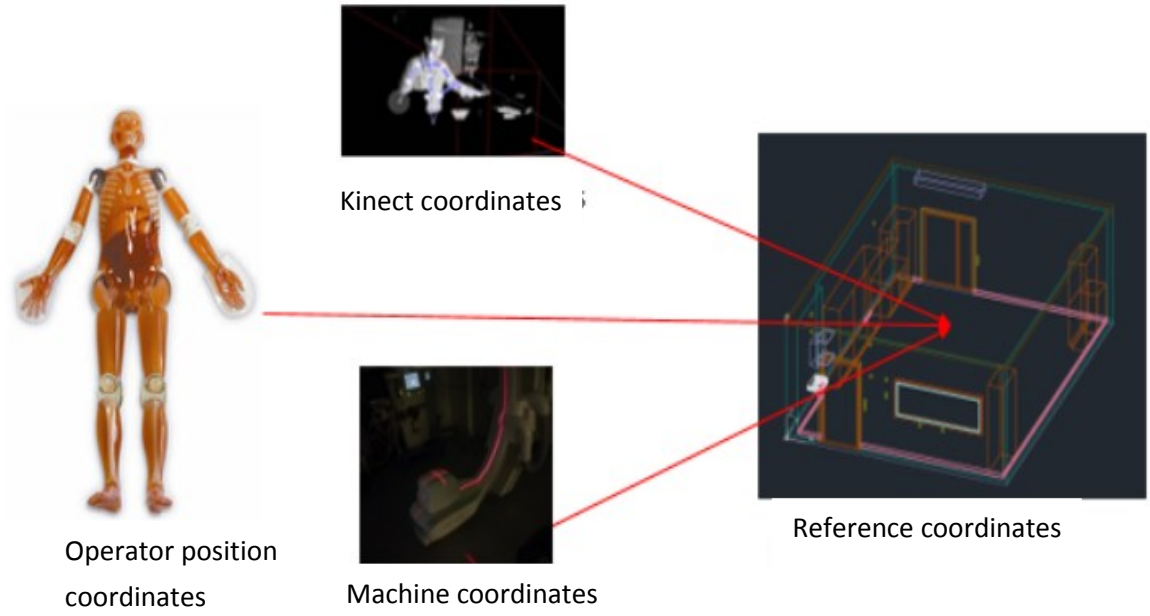


Figure 11. The different systems sending data to the IPS have separate coordinate system.

VII. Organ dose calculations

For this validation exercise, the calculations did not include calculations of organ dose. The measured values have been compared with measurements using personal dosimeters calibrated for personal dose equivalent Hp(10) or Hp(0.07).

VIII. Result of measurements and calculations in a controlled setting

A Kinect2.0 was mounted in the ceiling to track and record movement of different experimental set-ups. Schematic drawings of the operating room with dimensions and the position of the isocenter are shown in Figure 12. All experimental distances are measured with a laser rangefinder (Bosch GLM 100 C) with an accuracy of ± 1.5 mm.

Out of several measurements in a controlled setting, two different measurements are presented below. The first measurement (A) was performed to determine the exposure level for the operator at two different tube angles at two different operator positions and to validate the radiation dose that is given in the RDSR-file. The value of the calculated incident air-kerma at a fixed distance from the x-ray tube focus is included in the RDSR-file. This could be a good and accessible exposure value for converting relative values to absolute radiation dose values in the Monte Carlo-simulations for each independent exposure. The second measurement (B) was performed to validate the simulated values for a specific experimental set-up.

A. Validation of machine reference point and measurement of scattered radiation

The first measurement, to validate the reference point given in the RDSR-file, was performed with a semiconductor silicon detector (R100 Dose probe, RTI Technology) placed under the table couch at 89 cm. The measured air-kerma was recalculated to the reference point of the RDSR at 108 cm above the floor. Measurements were performed for two different gantry angles (0°, 15°). The “dose probe” detector was also placed on the anthropomorphic phantom (CT Torso Phantom CTU-41, Kyoto Kagaku) chest mimicking the main operator, at two different operator positions. To generate scatter radiation another anthropomorphic phantom (Adult ATOM® Dosimetry Verification Phantoms, Cirs) was placed on the table of the X-ray machine, acting as patient. Additional eye dose measurements were performed with Unfors Educational Direct Dosimeter (EDD-30). The setup is shown in Figure 12.

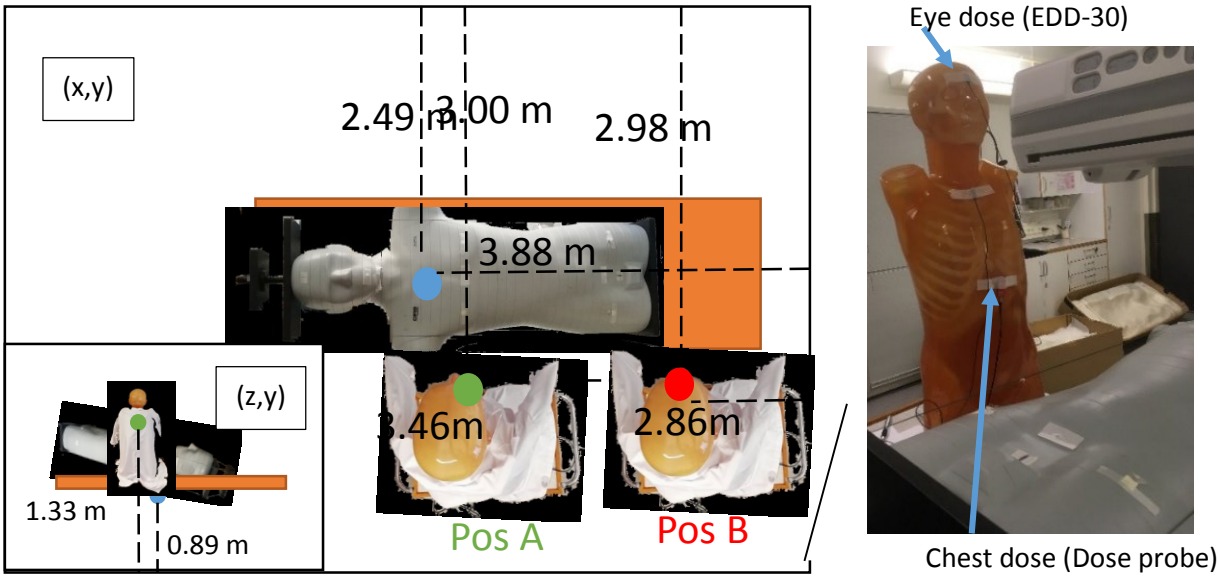


Figure 12. Left: The setup geometry of the first measurement. Green and Red: Detector placement on operator’s chest at position A and B Blue: Detector placement under patient (under table). Right: An image of setup geometry Pos A.

Table 2. Measured absorbed dose values from two different tube angles compared to the Reference point given in the RDSR-file.

	Angle (°)	POS A (µGy)	POS B (µGy)
Reference point (RDSR-file)	0	860	
Entrance dose recalculated to RP (Dose probe)	0	863	
Reference point (RDSR-file)	15	880	
Entrance dose recalculated to RP (Dose probe)	15	891	
Chest dose (Dose probe)	0	0.76	0.08
	15	1.25	0.11
Eye dose (EDD-30) ["Hp(3)", µSv]	0	0.48	0.27
	15	0.52	0.42

The results of the measurements are presented in Table 2. The values for the reference point given in the RDSR-file and the Dose probe measurements indicates that this parameter can be used as a conversion factor, when going from relative simulated Monte Carlo values to estimate the absolute absorbed dose to the operator. The difference is within 1% which is much lower than the required accuracy in personal dosimetry, as it will be shown in the following paragraph. The single image acquisitions measurement for the chest and eyes from scatter radiation shown in Table 2, are measured without using the movable ceiling-suspended shielding nor lead apron. For the 15° angle measurement, with the beam aimed away from the operator, the doses from scatter radiation are higher for both Pos A and Pos B. The measurement also shows that the effect on the scattered radiation produced when tilting the x-ray tube differ at different measurement heights. The radiation dose measured at chest height decreased from 1.25 µGy to 0.11 µGy when moving from pos A to pos B, the corresponding decrease at eye height is only from 0.52 µGy to 0.42 µGy. These measurements indicate that the scattered radiation is very inhomogeneous in all directions.

B. Validation of Monte Carlo simulation

The second measurement used a similar setup geometry as given in Figure 12, except for the position of the operator. A standard fluoroscopy mode – 4 pulses per second – was used. The dose probe detector was placed under the table. On the phantom, resembling the operator, were several TLD and active personal dosimeters positioned, Figure 13.

The personal dose equivalent Hp(10) and Hp(0.07) of the operator was measured using:

- UPC whole body personal dosemeters (4 Thermo Luminance Dosimeters, LiF:Mg,Cu,P type TLD 2000C). They will be referred in this text as TLD(UPC). The reference point of the TLD(UPC) is situated at the center of the back side of the dosemeter holder. The uncertainty of the TLD(UPC) measurements are of the order of 20% (k=2) for doses above 70 µSv. This value is calculated considering the uncertainty associated to the repeatability, energy and angular response and calibration factor at a reference energy.
- Thermo Electron Corp. type EPD MK, active personal dosemeters (Three silicon diodes). The dosemeter can provide Hp(10) and Hp(0.07) measurement but only Hp(10) was recorded. They will be referred in this text as EPD. The reference point of the EPD is situated at 12 mm from the back of the detector and centered at the beta detector position (orange filter). The uncertainty of the EPD MK reading are of the order of 22% (k=2) according to the manufacturer information, considering energy and angular response and the accuracy for Cs-137.

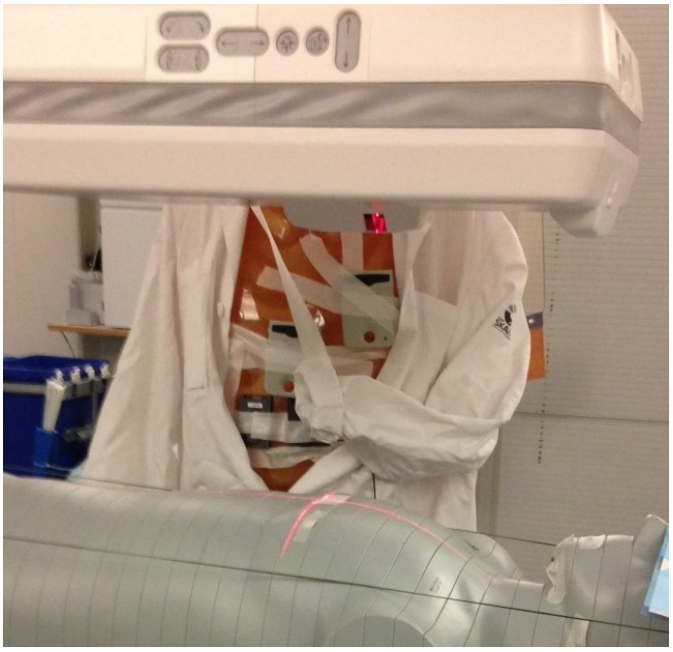


Figure 13. Experimental set-up (operator doses)

The patient entrance dose is determined using:

- KAP measurements registered in the RDSR file corrected by the field size at the patient entrance.
- R100 dose probe RTI Technology connected to a Cobia Flex electrometer. Provides air kerma and air kerma rate. This detector does not measure the contribution of the radiation backscatter.
- TLD(UPC) dosemeters. In this case a special calibration will be performed to refer the TL reading to air kerma. The uncertainty of the TLD(UPC) is of the order of 10% (k=2).

The measurements were conducted by three separate cases of irradiating to the phantom. All three cases were performed using fluoroscopy. For the first two cases the tube angle was at 0° and for the last case the tube angle was tilted 15°, with a beam direction aiming away from the operator. For the two latter cases the phantom was positioned closer to the X-ray tube, to increase the dose level for the detectors giving them a higher input signal.

Simulations are performed with PENELOPE/penEasy code, using the detection forcing technique. The main approximations applied were (figure 14):

- Patient phantom is replaced by a prism made of soft tissue (ICRU four-component).
- Patient Table is replaced by an equivalent thickness of Al.
- The floor and the walls of the room are not simulated.
- The position of the dosemeters is introduced manually during this validation test.
- At each position of interest (point B), Hp(10) is calculated as:

$$H_p(10)[\mu Sv] = N \cdot F \cdot \sum_{i=1}^{n} \phi_i^{sim} \cdot \left(\frac{\mu_{en}}{\rho}\right)_i \cdot E_i \cdot \left(\frac{H_p(10,0^{\circ})}{K_a}\right)_i \cdot \left(\frac{H_p(10,\alpha)}{H_p(10,0^{\circ})}\right)_i$$

where

- N is the normalization factor to refer the simulated absorbed dose per history to the real number of emitted photons, it is calculated from the ratio between the entrance air kerma (indicated by the RDSR) and the calculated air kerma (K_a) (point A).
- F is a unit normalization factor $1.602 \cdot 10^{-13}$ [J g kg^{-1}]
- ϕ_i^{sim} is simulated fluence, from Tally Photon Fluence Point, for energy region i at point B [cm^{-2} eV^{-1} per history].
- $\left(\frac{\mu_{en}}{\rho}\right)_i$ is mass energy-absorption coefficient for energy region i [cm^2 g^{-1}]
- E_i is middle energy for energy region i [eV].
- $\left(\frac{H_p(10,0^\circ)}{K_a}\right)_i$ is conversion coefficient from air kerma free-in-air to H_p(10,0º) in an ICRU slab for energy region i, interpolated from ICRP74[1].
- $\left(\frac{H_p(10,\alpha)}{H_p(10,0^\circ)}\right)_i$ is angular dependence factor for energy region i, interpolated from ICRP74[2].

Simulation time was 120 s with statistical uncertainties below 1% (k=2).

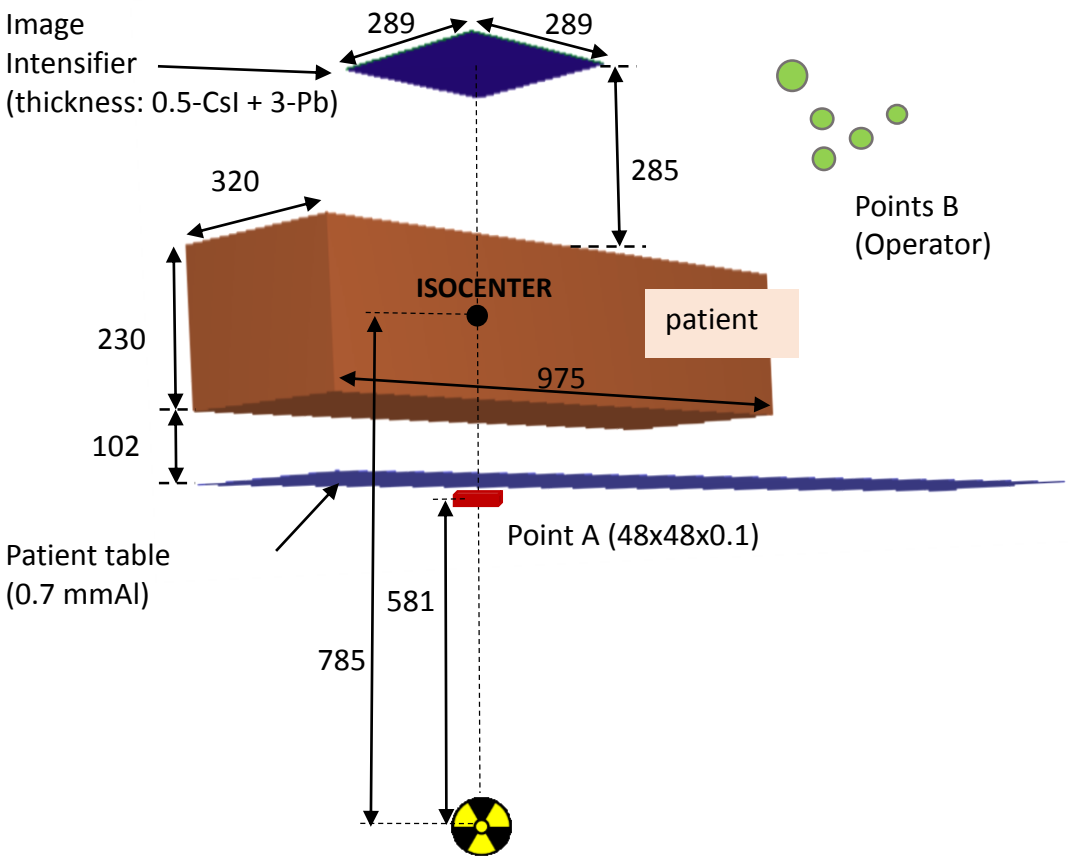


Figure 14. Simulation geometry, all values in mm (view obtained with gview3D)

[2] ICRP, 1996. Conversion Coefficients for use in Radiological Protection against External Radiation. ICRP Publication 74. Ann. ICRP 26 (3-4).

Entrance dose - results

Table 3 shows the KAP data from RDSR file of the X-ray output, the air kerma rate and air kerma measured with the R100 probe and the entrance dose measured with the TLD situated under the coach. The entrance air kerma derived from the KAP referred to the distances where the entrance dose is measured with the R100 and the TLD.

Table 3. Measured patient entrance doses.

Experiment no	Tube angle	RDSR KAP [Gy·m^2]	Entrance air kerma rate R100 [µGy/s]	Entrance air kerma RDSR [mGy]	Entrance air kerma R100 [mGy]	Entrance dose from TLD (UPC) [mGy]
1	0°	0.00028049	49.8	14.5	15.0	13.7±1.3
2	0°	0.00041026	265.0	21.2	22.4	20.2±1.7
3	15.1°	0.00042095	112.7	21.7	22.2	20.0±1.8

Differences below 10% are found when comparing the entrance dose derived from the RDSR and the measurements with the R100 probe and the TLDs. Considering the uncertainty associated with the energy response of the different detectors, this difference is considered acceptable. As a conclusion of this verification, the RDSR KAP value is used in the simulation to determine the operational quantities and an uncertainty of 10% is associated to this value. However, larger uncertainty could be present for other x-ray equipment and radiation qualities. And before using the PODIUM application, the accuracy of the KAP meter in the room must be checked.

Operator dose measurements $H_p(10)$ - results

Table 4 shows the $H_p(10)$ readings from the different personal dosemeters used in each experiment.

Table 4. Measured operator doses

Experiment No	Tube angle	$H_p(10)$ [µSv]			
		EPD-1 (nº20)	EPD-2 (nº9)	TLD (ref UPC)	TLD (refUPC)
1*	0°	11 ± 3	16 ± 4	9 ± 11 (DC16)	7 ± 6 (DC20)
2	0°	73 ± 16	72 ± 16	85 ± 15 (DC48)	134 ± 27 (DC52)
3	15.1°	73 ± 16	63 ± 14	105 ± 21 (DC36)	-

*The uncertainty of the TLD measurement in this experiment is of the order of 100% (k=2) because the dose is very low.

Simulation results

The following tables show the simulated Hp(10) compared with the experimental measurements for each detector and each experiment, including the associated uncertainty (k=2). In the case of Monte Carlo data the uncertainty takes into account the statistical uncertainty and an uncertainty of 10 % (k=2) associated to the air kerma value used in the normalization (Table 3).

Table 5. Simulated operator doses. Experiment 1

Experimental [µSv]				Simulation [µSv]			
EPD1	**EPD2**	**DC16**	**DC20**	**EPD1**	**EPD2**	**DC16**	**DC20**
11±3	16±4	9±11	7±6	13.3 ± 1.3	18.0 ± 1.8	12.8 ± 1.3	11.2 ±1.1

Table 6. Simulated operator doses. Experiment 2

Experimental [µSv]				Simulation [µSv]			
EPD1	**EPD2**	**DC52**	**DC48**	**EPD1**	**EPD2**	**DC52**	**DC48**
73±16	**72±16**	**134±27**	**85±15**	**106 ± 11**	**93± 9**	**130± 13**	**100± 10**

Table 7. Simulated operator doses. Experiment 3

Experimental [µSv]			Simulation [µSv]		
EPD1	**EPD2**	**DC36**	**EPD1**	**EPD2**	**DC36**
73±16	63±14	105±21	72 ± 7	63 ± 6	83± 8

The comparison between the measured and the simulated operator doses for each experiment and each type of dosemeter is summarized in Table 8, as the ratio of the simulated and the measured dose. The combined uncertainty of the simulated and measured value is also presented.

Table 8. Simulated vs measured operator doses and associated uncertainty

	Ratio: simulated/measured			
Experiment	EPD1	EPD2	TLD(UPC)1	TLD(UPC)2DC20
1	1.2±0.3	1.1±0.3	1.4±1.2	1.6±1.2
2	1.4±0.4	1.3±0.3	1.0±0.2	1.2±0.2
3	1.0±0.2	1.0±0.2	0.8±0.1	

The results are considered satisfactory for the purpose of the study. The mean value of the ratio obtained from the 6 EPDs measurements is of 1.18 and from the 5 TLDs of 1.19. The largest difference with TLDs is found for experiment 1, where the measured dose is very low, below reporting level (experimental uncertainty of 100%). For the other two experiments the difference is below 30%. In the case of the EPDs the largest difference, 40%, was found in one of the dosemeters in experiment 2.

These differences are consistent with the associated experimental differences mainly due to the energy response of the dosemeters in an unknown radiation field. In addition, for some of the cases, there could be an additional uncertainty associated to the position of the dosemeter. Changing 1 to 2 cm the position of the scoring point in the Monte Carlo simulation can produce a 10% difference in the dose.

The experiments organized within EURADOS WG12 comparing APDs and passive dosemeters worn together in hospitals during interventional procedures also showed differences of this order and higher for similar irradiation conditions.

IX. Conclusions and future work

The goal of the PODIUM project is to develop a user-friendly online tool to calculate radiation dose to workers among others in interventional radiology. This will be done by combining positioning information from individual staff members using an indoor positioning system based on the Kinect 3D camera as well as information on the radiation field and the geometry of the room. The Indoor position system (IPS) is developed in parallel to other systems and at the time of this validation a complete system is not available. Thus, this validation has been performed on the separate modules.

The investigations in a controlled setting have shown that the concept developed in PODIUM is promising and show feasibility in the clinical setting. The monitoring system (the Kinect camera) has to be placed in an optimal position. The investigation has shown that every operating room is unique and local knowledge about how the staff is working during the procedures must be known to be able to find a useful position.

The tracking system worked well, during this investigation in a controlled environment. However, using a one camera approach, during the clinical validation, there is a high probability that occlusions will occur and that the Kinects phantom tracking ID may switch from one staff member to another. This is especially the case if the staff will leave the operating room during image acquisitions and hence exit and re-enter the Kinect camera field of view. The possibility to include additional cameras in the room to avoid black spots due to moveable objects is being explored. Still, in some situations and rooms, one camera may be sufficient to track the main operator.

For the calculations, reliable dose data from the x-ray machine are needed. The most reliable way to access these machine parameters would be to access the RDSR report. In the validation, the RDSR report was exported after all measurements were performed. To perform online dosimetry the on-line tool needs to have access to RDSR-data instantly from the X-ray machine. However, to be able to connect to the X-ray machines and get instant access to this information would add complexity and there would be a need to work closely with vendors as future work of the project.

The comparison between calculations and measurements indicates that the simulation generates reasonable values and with a reasonable uncertainty regarding the systems scope of application.

In the controlled experiment there are some parts which have not been included in the validation. The X-ray machines are equipped with movable ceiling-suspended radiation shielding which can be positioned between the operator and the radiation beam. When the clinical validation is performed, the IPS should be able to track the position of such shields, as its position will have an effect of the dose to the operator.

This investigation and measurements suggest that the on-line software tool needs a thorough validation and testing process when the modules are finished and the first release of the system is available to the project partners.