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Lead Authors: Filip Vanhavere, Maria Amor Duch, Maria Zankl, Olivier Van Hoey, Anja Almèn, Una O’Connor, Rick Tanner, Eleftheria Carinou


Reviewer(s): Filip Vanhavere
and CONCERT coordination team

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Executive summary: PODIUM: Personal Online Dosimetry Using computational Methods

Monitoring the individual exposure of workers constitutes an integral part of any radiation protection programme. At present, personal dosimetry is typically performed by issuing staff with physical dosemeters. The objective of PODIUM was to improve occupational dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosemeters. Operational quantities and protection quantities can, in theory, be assessed based on the use of modern technology such as personal tracking devices and flexible individualized phantoms. When combined with fast simulation codes, personal dosimetry could be possible in real-time. PODIUM can be considered a feasibility project to take the first steps towards such a novel dosimetric approach.

The availability of the proposed online personal dosimetry approach can overcome the problems that arise from the use of current passive and active dosemeters. Such limitations include the uncertainty in assessing neutron and photon doses, especially when part of the body is shielded, the delay in calculating the doses and the situation where workers position dosemeters incorrectly. In addition, it will increase awareness of radiation protection among workers and improve the application of the ALARA principle.

This PODIUM approach was performed using a combination of (i) monitoring of the position of workers in real time and (ii) the spatial radiation field, including its energy and angular distribution. The movement of workers needs to be monitored by modern cameras and software. The radiation field map of the workplace can be based on analytical calculations or more advanced Monte Carlo (MC) calculations. A variety of computational body phantoms can be used, assuming various postures inside the radiation field and having different body statures. Because of the limited time frame, an intermediate approach with pre-calculated fluence to dose conversion coefficients for phantoms of different statures and postures was also used. The methodology was applied and validated for two situations where improvements in dosimetry are urgently needed: neutron and interventional radiology workplaces.

In the course of the project we have set up two indoor position systems (IPS) to track monitored people. The first system is based on the use of a Microsoft Kinect 2.0 depth sensor camera with adapted software. The second system is a two-camera solution based on the use of two Kinect 2.0 depth sensor cameras and adapted software. This advanced solution is capable of fusing the images from the two cameras and thus can reduce occlusion problems and increase the field of view of the cameras. Both systems were finalized by the end of the project; however, some improvements are needed such as the tracking of objects like the ceiling-mounted lead shielding or the X-ray system C-arm, which are needed, if used, for the dose calculations.

In PODIUM we have developed a set of computational phantoms with a range of anatomies and postures. Furthermore, we have provided a library of pre-calculated fluence to dose conversion coefficients for phantoms having reference statures and non-reference postures, as well as for phantoms having various statures that can be used as a first approach of the fast, online dosimetry application for workers in realistic workplaces.

As regards interventional radiology/cardiology workplaces the required information and data sources have been identified. In particular, for the calculations the most reliable way to gather the required information is from the Radiation Dose Structured Report (RDSR).

Two fast MC systems have been developed for application in hospitals during interventional radiology procedures. The two codes have been tested and provide acceptable results with simulation times that can be lower than 20 s (CPU/GPU use time) per simulated irradiation event. The developments described above were combined in a user-friendly application to allow non-specialist users to assess and follow up staff doses.
The PODIUM Dosimetry online Calculation Application (DCA) allows users to calculate individual occupational doses for staff in interventional rooms. The technical modules for staff tracking and dose calculation were developed as external modules, all connected with the DCA. A partial set of first tests using the DCA in clinical practice was completed because the DCA was still under development in parallel to other project tasks. However, more testing in clinical practice with the final DCA version is ongoing.

For the validation of our system in interventional radiology, a series of fixed experimental set-ups was first used in a systematic manner in a hospital. The validation experiments were performed using clinical X-ray equipment, where X-ray field size and tilting of the X-ray tube was altered. The operator was simulated using phantoms. During the experimental set-ups, detailed measurements, from different positions using active and passive dosemeters on anthropomorphic phantoms, were performed in order to validate the computed doses. The measurements gave useful information to improve the simulations, source specifications and geometry mapping.

Secondly, a full-scale feasibility test in clinical settings during real patient treatment in hospitals was performed. Different fluoroscopically guided procedures were chosen including commonly performed vascular and cardiovascular procedures. The staff dose of different body parts were measured using active and passive dosemeters on relevant positions on the operators. The clinical environment is necessary in order to gather appropriate information on the performance of an online dosimetry application in the hospital, as the interventional radiology / cardiology environment is one of the most complex situations for personal dosimetry.

For neutrons, the real time Monte Carlo method is not feasible due to the time constrains being unrealistic for such computationally intensive simulations, as well as problems with the calculation method itself. Therefore, only the lookup method was used. The optimization and validation was first done in an easy accessible simulated workplace field in a calibration laboratory. Secondly, a real workplace was tested with a nuclear fuel rod container. For both fields, extensive efforts were done to model the mixed photon-neutron radiation field, and this was compared with mapping through measurements. The different quantities \( E, H_p(10), H^*(10) \) were used in the mapping, which proved very challenging because it requires the energy and angular distribution of the radiation field. These maps were combined with the tracking data of the moving workers in the workplace to estimate their doses. Comparisons with measurements from individual neutron dosemeters showed the clear advantages of the PODIUM system. The more effort is put in getting the correct dose map, the more accurate the dose estimation. However, even for very basic simulations, or just with mapping generated by ambient monitors, the PODIUM results provide better accuracy results than the presently existing neutron personal dosemeters.

PODIUM is perceived as an innovative way forward. The PODIUM applications have the potential to be brought to the market using it as a training tool or as individual dosimetry option. An exploitation plan was set-up during the project. The PODIUM approach can be implemented in various fields, like medical applications, industrial facilities, nuclear industry and even radiation dosimetry in space. At present the technology readiness level (TRL) is 3-5, depending on the application field, and it requires a second phase to complete its demonstration to a TRL of 8 or 9.

In conclusion, PODIUM proved the feasibility of performing personal dosimetry of occupationally exposed workers using computational methods. Applying this novel approach would give significant advantages compared to present physical dosemeters, with possible first use as an ALARA tool. However, Future improvements will certainly pave the way for the application of the innovative PODIUM approach as an approved dosimetry service.
Introduction

Monitoring the individual exposure of workers constitutes an integral part of any radiation protection programme. Individual monitoring of exposed workers to external ionizing radiation is essential in order to ensure safe and satisfactory working conditions; demonstrate compliance with dose limits and the application of the ALARA principle. At present, personal dosimetry is typically performed by issuing staff with physical dosemeters.

The physical dosemeter is designed to measure the operational quantity $H_p(10)$ as an estimate of the effective dose, $E$. In some workplaces several additional dosemeters are required to assess $H_p(0.07)$ as an estimate of the skin or extremities equivalent dose or $H_p(3)$ as an estimate of the equivalent dose to the lens of the eye or to take into account the shielded and unshielded parts of the body. These physical measurement devices are part of routine practice, but still have many limitations, both from a practical and from a metrological point of view. The results are usually known only after some delay with passive dosemeters (30-60 days). In addition, performing precise and reliable personal dose measurements in all types of workplaces is quite difficult. There are issues with compliance and multiple dosemeters can be mixed up or worn incorrectly. The number and positioning of individual dosemeters is becoming more complex with the new focus on eye lens dosimetry. Also, the uncertainties with the present dosemeters are not negligible. An uncertainty factor of 2 is accepted as good practice for low doses and for neutron fields in particular the uncertainties are even higher.

Recent developments are moving towards active personal dosemeters (APDs) and to active systems that can transfer the dose data to online applications (smartphones, servers). This would improve the application of the ALARA principle. However, APD technology has not yet been proved to be sufficiently accurate in some fields such as pulsed and neutron radiation fields. Also, it still requires the use of physical dosemeters and its associated problems.

On the other hand, computational techniques are evolving rapidly. In the past, standard mathematical phantoms were used, while now very detailed voxel and Non-Uniform Rational B-splines (NURBS) phantoms are available. In addition, with increasing computational power, such calculations can be performed faster and faster.

The objective of this proposal is to develop a user-friendly online application to calculate workers’ doses in real time. Instead of measuring individual doses with a physical dosemeter, doses will be calculated.

A validation and proof of concept of the proposed methodology will be done in two fields that could most benefit of the advantages of this methodology: interventional radiology and workplaces with mixed neutron/photon fields.

Interventional radiology and image-guided treatments are areas in the medical sector that could gain from applying the proposed online application. The type of X-ray equipment, the patient workload, the use of radiation shielding and staff position varies depending on the interventional procedure and this has a big influence on staff doses. Monitoring staff is difficult, especially for the unshielded body parts such as the head, eyes and extremities. Thus, reliable dose assessments for different parts of the body are very much needed. The importance of eye lens dosimetry has been emphasised with the publication of the new EU Basic Safety Standard. Detailed real-time information of the dose distribution over the whole of the operator’s body during patient treatment could enhance the possibility for optimized protection. Radiation dose monitoring systems in this particular area need improvement and the output of this project would surely add value to the radiation protection in a clinical environment.

Neutron dosimetry in the workplace is a particularly difficult problem, because of the wide energy range of the neutrons encountered (meV to MeV in conventional workplaces), the strong energy dependence of the neutron cross-sections, the consequent strong energy and direction dependence of the fluence to dose equivalent conversion coefficients, and the strong scattered component found in most workplace fields. In
addition, the actual routinely measured $H_a(10)$ values usually lie below 300 microSv, where accuracy is even more difficult to achieve. Despite many years of development, neutron personal dosemeters and survey instruments still present deficiencies for an accurate measurement of neutron doses. It is expected that no simple good technological solution can be found soon for this. The proposed methodology aims at providing reliable and online personal dosimetry for workers in mixed neutron/gamma fields which is not available currently with the standard techniques. Thus, the present project is especially relevant for these workplaces.

**General goal**

The objective of this project is to improve occupational dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosemeters. Operational quantities and protection quantities and even radiosensitive organ doses (e.g. eye lens, extremities) will be assessed based on the use of modern technology such as personal tracking devices and flexible individualized phantoms. When combined with fast simulation codes, the aim is to perform personal dosimetry in real-time. This will be done using a combination of (i) monitoring of the position of workers in real time and (ii) the spatial radiation field, including its energy and angular distribution. The movement of workers needs to be monitored and transferred to a calculation application. Modern cameras and software will be used for this. Such devices are used in the gaming industry, but are not yet applied in radiation protection. The radiation field map of the workplace can be based on analytical calculations or more advanced Monte Carlo calculations. A variety of computational body phantoms will be used, assuming various postures inside the radiation field and having different body statures, so that also organ doses can be determined. Because of the limited time frame, we will simultaneously use an intermediate approach with pre-calculated fluence to dose conversion coefficients for phantoms of different statures and postures. This approach will provide us with the first step towards online dosimetry based on simulations.

This proposed methodology for personal dosimetry for workers is very innovative and challenging. It will explore a new direction in personal dosimetry and, as such, will add value to the radiation protection community and regulatory system. In addition, the proposed approach can be used for ALARA optimization, as well as for education and training activities. It overcomes the errors and challenges of current personal dosimetry such as, dosemeters not worn or worn incorrectly; physical damage during use; “malicious” exposure of dosemeters; radiation field not well defined; defective or badly processed dosemeter; dosemeter with poor response for the energy and direction of the radiation field. Since protection quantities could be used directly, it could even help in overcoming all the problems associated with the use and definition of operational quantities. The legal aspects to introduce this or similar techniques as an official dosimetry method will also be established.

**Structure of the project**

The project is structured into 7 work packages (WP), WP0 for the management and coordination tasks and 6 WPs for specific tasks leading to the main objective, which is to improve occupational dosimetry by the development of an online dosimetry application based on computer simulation.
The project structure, WP interactions and partner participation in each WP is shown below.

![Project Structure Diagram]

**Project Management**

WP0 ensured the day-to-day project management activities

- Take care of all project management activities, including the overall scientific follow-up
- Keep track of the time schedule and the milestones
- Coordinate consortium meetings and making the minutes
- Manage financial, administrative and contractual aspects
- Assess risks in a structured and targeted manner and set up a contingency plan
- Be responsible for the communication with CONCERT
- Ensure IPR and knowledge management as well as ethics management

**Project management, internal communication, financial and administrative management, meeting coordination**

During the PODIUM project, 6 meetings were organised:

- Kick off meeting, Mol: 24-26/01/2018
- Second meeting, Munich: 25-26/05/2018
- Third meeting, Malmo: 5-7/11/2018
- Fourth meeting, Dublin: 12-14/3/2019
- Fifth meeting: Barcelona: 2-4/9/2019
- Sixth meeting, Athens (together with PODIUM workshop): 25-29/11/2019

In between, webmeetings were organised with all partners on 7/3/18, 18/4/18, 24/5/18, 4/9/18, 18/12/18, 5/2/19, 17/4/19, 5/6/19, 7/11/19, 12/12/19. From each of these meetings extensive minutes were prepared. Next to these there were plenty of webmeeting dedicated to specific work packages.

The PODIUM management structure was established at the beginning of the project. One representative from each partner forms the Project Management Board (PMB), which was responsible for decision-making.
Deliverable D1.121
during the project. This PMB monitored the progress of the project and the work done by the different partners. Some shifts in budget from one partner to another were also decided by the PMB. The PMB has met during each meeting, and separate minutes have been made from these PMB meetings.

From the beginning of the project, a website was established by SCK•CEN. It contains a public part with general information and with links to all public deliverables. It also includes a secure sharepoint part where all working documents are stored and shared between the partners. The secured area also includes a discussion forum where most of the conversations between partners are held.

CONCERT communication, reporting, knowledge management, IPR management
The IPR and knowledge management are fixed through the consortium agreement, which was finalized and signed by all partners. As regards exploitation activities, work package 6 set up an exploitation plan that will guide the consortium in the identification and subsequent leverage of exploitable project results.

This task 0.2 also involves the review and final approval of all deliverables. The following deliverables were submitted and accepted, and they are all publically available:

- D9.101: Report listing all requirements of the software (M1)
- D9.102: Detailed specification of the fields to be used (M3).
- D9.103: An IPS based on an infrared reflection time-of-flight sensor camera together with the corresponding software (M6).
- D9.104: Database of phantoms of different statures and postures (M9).
- D9.105: An IPS based on a developed camera network system and the multi-image acquisition computer system with the corresponding software (M12).
- D9.106: Prototype of fast MC real time radiation dose estimate application to be tested in hospitals (M24)
- D9.107, part A: Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application. Part 1: Workplace geometry (M12).
- D9.107, part B: Guidelines for implementing the workplace geometry and the radiation field map in the dosimetry application. Part 2: Radiation Field Map (M18).
- D9.109: First annual report (M12)
- D9.110: Validation of the application in a controlled experiment set-up in a hospital (M14)
- D9.112: Criteria for the approval of online dosimetry as legal dosimetry system (M18).
- D9.113: Report from the feasibility study performed in two hospitals (M22).
- D9.114: Report summarizing the experimental and clinical findings when using the online dosimetry application (M23).
- D9.115: Workshop (M23)
- D9.116: Fluence to dose conversion coefficients for reference phantoms and postures other than standing for photons and neutrons (M24).
- D9.118: User-friendly online application + manual (M24)
- D9.119: Report summarizing the computational developments needed to realize full online dosimetry using simulation of voxel phantoms in the workplace. (M24)
- D9.120: Exploitation plan (M24)
- D9.121: Final report (M24)
WP1: Dose simulations input: staff movement monitoring and radiation field mapping

Task 1.1: Development of an indoor position system

The objective of the indoor positioning system (IPS) is to monitor the position of workers in order to calculate their doses. Ideally, the information should be in real time, but within the framework of PODIUM, in most cases, the radiation field was not known in real time and thus, off-line calculations of the IPS output information were also considered.

This session describes the requirements for the IPS to be used in PODIUM, the type of sensor selected and the two tracking options developed and tested in the project. The first option is based on the use of a single sensor [1] and it was chosen mainly because of its ease of use and ease acceptability in the workplaces. The second solution is a multi-sensor proposal and it has been tested with two sensors [2]. Most of the results shown in WP4 and WP5 were obtained using the single sensor solution. Both proposals were improved during the project, as they were tested in order to solve the difficulties found in practice.

I. Requirements for the IPS

The indoor positioning system (IPS) for PODIUM must be able to recognize the presence of a human body (or more than one) in a workplace, identify its posture and measure with accuracy the position of relevant human joints in 3-Dimensions, in real-time. The definition of relevant joints depends on the application where the online dosimetry system is used. They may include chest, legs, head, arms, and even hands for those applications where the radiation field is very inhomogeneous. Regarding the requirements of accuracy, the maximum geometrical error in the tracking depends on the distance from the source. In most cases, a geometrical error of about 10 cm should be sufficient; such accuracy should guarantee that the uncertainty in the dose assessment will be substantially lower than that of current physical dosimeters. Further away from the source, even lower accuracies would be sufficient.

The IPS must be able to monitor workers moving within an area of about 10-15 m² for the applications of PODIUM WP4, i.e. Interventional Radiology (IR) and for most of the cases considered in PODIUM WP5, where the workers are in close proximity of a neutron source, such as, nuclear workers handling a canister with spent nuclear fuel. The third requirement for the IPS is that it must be able to provide, in real-time, the required data to the dose calculation modules of the online dosimetry system. Lastly, but not less important, the IPS must be simple, reliable and non-invasive, i.e. marker-less. Once installed, the IPS must not constitute an impediment for the workers or a potential source of danger. Ideally, once set-up, the hardware and the software of the IPS must be able to run for several hours per day without necessity of any intervention. The simplicity aspect has also implications on the cost of the online dosimetry system of PODIUM. Supposing that the online dosimetry tool will be allowed as an official dosimetry method, the IPS should be cost-effective to compete with conventional physical dosimeters.

In the framework of PODIUM, as a feasibility study, it was decided to monitor the dose of one single person per workplace, and thus the tracking had to send to the application only the information of this person.

II. Description of the selected IPS: Kinect v.2

Tracking methods based on Computer Vision (CV) are the ideal approach for achieving PODIUM requirements. Currently, various CV technologies are available for tracking human bodies. Some of them make use of traditional type of camera sensors, like optical photo-cameras. The most complex and advanced
methods, instead, make use of depth sensors that can create 3-Dimensional images of a scene. RGB standard cameras do not provide directly 3D data. However, 3D data can be inferred or calculated from a multi-view solution (2 cameras or more). But it requires expensive hardware to extract body parts in real time. On the other hand, depth cameras provide directly 3D coordinates of present objects related to camera position. Body parts position can be obtained with a standard PC. Tracking technologies based on depth camera fulfill better the PODIUM requirements and they were chosen for the project.

Depth cameras can build real-time 3D maps of the scene in its field-of-view (FOV), with frame rates up to tens of hertz. Structured light, Time-Of-Flight (TOF) and stereo camera are some of the most prominent methodology used for depth cameras. Among them, we evaluated that the TOF technology is the one offering the optimal compromise between geometrical accuracy, speed, maximum range in depth and cost of the depth camera. The other technologies would be either very expensive (like stereo camera), either less accurate and with smaller tracking range (like structured light).

The most famous and widespread TOF camera is the KINECT v.2. The KINECT was designed by Microsoft as an economical consumer-grade device for human-machine interaction. The KINECT v.2 algorithm can track up to six human bodies within a distance of 4.5 meters from the camera; with an opportune placement, the KINECT v.2 can easily monitor 10-15 m² around a radiation source. Together with the device, Microsoft released a Software Development Kit (SDK), i.e. a rich collection of libraries which can be used to create software. The existence of the KINECT SDK is a key point, since it allows creating personalized programs making use of all the KINECT v.2 features (including the depth sensor and the recognition algorithm) and, at the same time, to generate personalized output files including the tracking information of all the relevant human joints, in a structured table format. After several years of improvements, the SDK has reached a high level of reliability, which means, for our IPS program, high stability and high performances. The geometric error of this device is estimated to be about 1-3 cm, which is more than sufficient for achieving the minimum requirements of the IPS. Finally, the TOF sensor of the KINECT and the recognition algorithm are very fast, even on a standard computer, and they can provide real-time tracking with frame-rates up to 30 Hz. Based on these characteristics and on the objectives of PODIUM, the KINECT v.2 TOF camera was chosen for developing the first PODIUM IPS.

The KINECT v.2 makes use of two sensors: an RGB camera for acquiring conventional RGB images (for pictures or videos, with a maximum resolution of 1920 × 1080 pixels) and a depth sensing module. Figure 1.1 shows a visual exemplification of the FOV of the 2 types of cameras in the KINECT. It should be noted that the FOV of the RGB camera is wider and shorter compared to that of the depth sensor. The FOV of the depth sensor has an aperture of 60° and 70° in vertical and horizontal directions, respectively, while the FOV of the RGB sensor has an aperture of 54° and 84° in vertical and horizontal directions, respectively.

The depth sensing module is constituted by an IR laser and by an IR camera with a resolution of 512 × 424 pixels. The laser illuminates the scene by emitting pulsed Infra-Red (IR) light, while the IR camera scores IR photons bouncing back after a reflection. Differently from the most common depth sensing technology based on structured light, KINECT v.2 calculates depth distances by measuring the phase shift associated to the reflected IR light on a pixel by pixel basis. The use of an IR illuminator means that the KINECT tracking algorithm can work even when the lighting conditions in the workplace are poor. The phase shift method, also known as TOF, allows the camera to reach a good compromise between range of the depth sensor, spatial accuracy, and high framerate. The camera generates colour and depth images with rates up to 30 frames per second, which is much higher than what is needed for tracking radiation workers.
Figure 1.1: Field-Of-Views (FOVs) of the RGB and depth sensors of the KINECT v.2, and dimensions of the tracking areas. The ideal position of the tracked persons is between 1.5 m and 4.5 m.

III. IPS based on a single Kinect camera

III.1 Specifications of the IPS acquisition software KDA

The IPS is operated through a software package consisting of two main programs, developed by SCK•CEN. The first program is used for the calibration of the system and it is meant to be used only once, after the IPS has been set-up in the workplace. The second program, named KINECT Data Acquisition (KDA), controls the acquisition and the storing of the tracking data. Since the programs make use of special API(s) (libraries) and drivers for connecting to the KINECT, it is necessary to install a series of software to execute them correctly. Both of the IPS programs make use of the software development kit of the device, i.e. the “KINECT for Windows SDK 2.0”. Due to the SDK requirements, only computers running Windows 8 (or more recent) and equipped with USB 3 port will be able to connect the device and make use of the IPS software. Additionally, the IPS software makes use of some well-known Open Source libraries, like OpenTK, Emgu CV, Office Open XML and EPPlus. These libraries are used for processing the tracking data and for exporting it in table format. KDA controls the acquisition of RGB and depth images, and it performs the KINECT recognition algorithm for identifying bodies and body parts on the depth images. Figure 1.2 shows the start screen with the acquisition settings, and the interface of the program while acquiring tracking data. The source code of KDA is made of a series of functions for acquiring and synchronizing the RGB and the depth images, and the recognition of body parts. Some of the functions are based on the KINECT SDK, while some others were programmed from scratch. While most of the source code was written in C# language, the graphic interface was written in XAML, to make use of the Windows Presentation Foundation (WPF) graphical subsystem.
Figure 1.2 shows in green a *skeleton object* obtained by the KDA. This object is a sort of simplified virtual skeleton which stores the 3-Dimensional postural data and its variation in time. The skeleton object consists of an array of 25 joints arranged according to a kinematic chain which is consistent with the kinematic of the real human body. Figure 1.3 shows the joints and *virtual bones* connecting the joints. Each joint is tracked separately but according to the kinematic chain, and its corresponding C# object can be accessed independently to retrieve the corresponding spatial information. The KINECT v.2 algorithm includes, as well, a joint prediction model, which can be used to provide estimated joint positions when the view is partially occluded. KDA makes use of the prediction algorithm, but at the same time it keeps track of when it is applied. This is done by associating a tally parameter to each joint (Joint_inferred), which scores the level of confidence of the prediction algorithm. Thanks to the tally, it is easy for us to filter a tracked joint when its position is not inferred correctly by the prediction algorithm.

The main objective of the IPS is the creation of real-time tracking data, which will feed the dose calculation programs of the PODIUM online dosimetry system. The real-time tracking data is provided by KDA in form of a table in an output file. For each frame, a time stamp, the body ID, and the corresponding X,Y and Z coordinates of all body joints are appended at the end of the output file, which is constantly refreshing during an acquisition. Figure 1.4 shows a sample of the extracted information in CSV format. The use of a table format allows to easily filter the tracking data to extract coordinates in a way that is convenient to the dose calculation modules.
Figure 1.3: Overview of the 25 joints tracked by the KINECT v2 and corresponding index used for the skeletal tracking.

![Diagram of joint tracking](image)

Figure 1.4: Example of KDA output file in CSV format. The file includes the collection of 3-Dimensional positions for each the 25 joints constituting the skeletal object, with a sampling rate of 1 Hz.

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>BodyID</th>
<th>SpineBase_X</th>
<th>SpineBase_Y</th>
<th>SpineBase_Z</th>
<th>SpineBase_inferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-Nov-2019 05:54:22</td>
<td>3</td>
<td>0.3123473</td>
<td>-0.28843</td>
<td>1.987383</td>
<td>1</td>
</tr>
<tr>
<td>21-Nov-2019 05:54:23</td>
<td>3</td>
<td>0.3129034</td>
<td>-0.289163</td>
<td>1.987671</td>
<td>1</td>
</tr>
<tr>
<td>21-Nov-2019 05:54:24</td>
<td>3</td>
<td>0.3587386</td>
<td>-0.3128628</td>
<td>1.940662</td>
<td>1</td>
</tr>
<tr>
<td>21-Nov-2019 05:54:25</td>
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<td>1.889573</td>
<td>1</td>
</tr>
<tr>
<td>21-Nov-2019 05:54:26</td>
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<td>0.6218299</td>
<td>-0.7262929</td>
<td>1.224977</td>
<td>0</td>
</tr>
</tbody>
</table>

This output file is the only data that is actually recorded by KDA; while the interface shows the live video stream from the KINECT, the program does not store any image (nor depth, nor RGB). Within PODIUM, this is important because it makes it easier to ensure privacy and compliance with the General Data Protection Regulation (GDPR).

KDA can be run as a standalone application, with its own interface, or, through the PODIUM application (WP3 section).

**III.2 Calibration of the single KINECT IPS**

The raw data from the IPS consists of the coordinates of the joints expressed only relatively to the camera coordinate system. When changing the position and the orientation angle of the camera, the joints coordinates will change accordingly. Therefore, the tracking data cannot be used directly to extract the actual positions and postures of the workers with respect to the workplace, which is the real-world coordinate system. So, for using the tracking data in our online dosimetry system, we need to transform the camera coordinates to real-world coordinates. This is done by means of a calibration process, which estimates the IR camera parameters for defining the camera coordinate system. The calibration process is performed only...
once, after fixing the camera location and orientation in a given workplace. In PODIUM, the reference point is placed at the C-Arm centre of rotation (isocentre) for the interventional set-up.

The camera parameters include intrinsics, extrinsics, and distortion coefficients. To estimate the camera parameters, one must detect 3D world points from the depth camera and then identify their corresponding 2D image points with the optical sensor. We can get these correspondences using multiple images of a calibration pattern, such as a checkerboard or a QR pattern. Using these correspondences between pixels from the depth and RGB images, we can solve a system of equations for the camera parameters.

To achieve this objective, SCK•CEN developed a calibration program to ease the calibration when setting the IPS in new workplaces or when the camera was moved. Figure 1.5 shows a schematic representation which wraps up the calibration when applied to a tracked skeleton object.

![Diagram showing calibration procedure](image)

**Figure 1.5:** Scheme showing how the calibration procedure allows to transform the coordinate system from the KINECT (i.e. camera-coordinate system) to any reference point (i.e. word-coordinate system)

### III.3 Filtering

Kinect v.2 sensor is not free from characteristic noise, which affects the joint position estimation even when the tracking conditions are good. During our tracking experiments, the Kinect sensor exhibits a permanent precision error in joints’ coordinates in the form of some little fluctuations of few centimetres (the exact dimension depends on distance), known as jittering. This joint jittering is a well-known problem for such tracking systems, and it is due to the tracking algorithm and to the noise of the depth images. So, we can consider this noise as a relatively small white noise that is always present for all joints and caused by imprecision. However, there exists another big source of noise mostly due to skeleton’s joints occlusion or self-occlusion which generates lack of accuracy. Even during stationary pose, some joints often appear to be shifted in unrealistic manner. These sudden joints’ coordinate changes are known as *spikes*. Thus, an important step before using the raw joint data is to remove as much noise as possible from the input data by means of a noise reduction noise filter. Since the noises have different characteristics, different filtering techniques should be used for each of them, in order to achieve good results. In order to study the nature of the noises and their frequency, the evolutions of X, Y and Z coordinates of each joint were analysed, as well as their first and second derivatives.
In an IPS, any smoothing strategy will introduce a lag or delay in the output increasing system latency. Latency in our application can be defined as how much time it takes for filter output to catch up with the actual joint position when there is a movement in a joint. Thus, latency degrades the synchronization of the person tracking and can jeopardize the accuracy of our real-time dose calculation. In general, the filtering delay depends on how quickly the input is changing, and hence, one cannot attribute a specific delay value to a given filter for all cases. However, this is a parameter that was considered when comparing filtering techniques. Different filters were tested before deciding upon which one to apply to our data [3]. We applied them using various permutations like applying median filter before and after exponential smoothing, different values of alpha, different window lengths for median filter, etc... A good filtering solution is usually a combination of various filtering techniques, which may include applying a jitter removal filter to remove spike noise, a smoothing filter, and a forecasting filter to reduce latency, and then adjusting the outputs based on person kinematics and anatomy to avoid awkward cases caused by overshoot [4]. We implemented a filter architecture that integrates jitter reduction, as well as statistical smoothing based on Holt Double exponential method [5] as described in the scheme of Figure 1.6. This implementation was provided natively in later versions of Microsoft Kinect version 1 SDK, but was yet to be implemented to version 2 SDK. It is highly configurable using simple configuration options.

The configuration of the filtration algorithm is highly dependent on the application and the nature of movement. Experimentation is required on an application-by-application basis in order to provide the required level of filtering and smoothing for each application requirement. In fact, this configurable implementation was designed to enhance the user experience in video games; thus very low latency configuration was set by default in the Microsoft SDK v1. On the other hand, for our application, we established that one frame per second rate is good enough to estimate doses to workers. Therefore, we set the filter parameters according to the following criterion:

- Applying jitter radius equivalent to the maximum distance between two consecutive joints.
- Avoiding aggressive smoothing which may cause inaccurate joint positions.
- Avoiding lags so that the filter output can be synchronized with the acquisition time.
Table 1.1 shows the proposed filter parameters obtained by trial and error.

**Table 1.1.** Double exponential filter parameters used for the selected filtering solution.

<table>
<thead>
<tr>
<th>Proposed Filter Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoothing coefficient</td>
<td>0.8</td>
</tr>
<tr>
<td>Correction factor</td>
<td>0.1</td>
</tr>
<tr>
<td>Prediction coefficient</td>
<td>0.25</td>
</tr>
<tr>
<td>Jitter radius</td>
<td>0.5</td>
</tr>
<tr>
<td>Max. deviation radius</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The advantage of the algorithm is that it will not introduce lags, which could cause a desynchronization in the acquisition time. Figure 1.7 shows an example of raw data of the hand from a real procedure once the proposed filter is applied.

**Figure 1.7.** Example of application of the selected filtering solution to the right hand tracking during a real X-ray procedure

### III.4 Solution to occlusion problems and users’ misidentifications

An important limitation of a multi-user tracking with a single Kinect is that the current tracking software does not provide an algorithm for identifying individuals. Recognizing the different users in different locations is an important and challenging task. Marker-less identification methods can be coarsely grouped, according to the used data, into three classes: RGB appearance-based identification, depth-based identification and skeleton-based identification. Most of the existing algorithms rely on RGB-based appearance features, for example references [6] and [7]. Nevertheless, RGB sources suffer always from pose changes, occlusions, clothes change (using of personal protection equipment, glasses,…etc.) and illumination variations. Facial recognition, for example, is particularly difficult in interventional radiology where monitored workers are usually wearing protective glasses and caps. Moreover, in PODIUM applications, in interventional radiology
and in selected neutron workplaces, the use of RGB appearance-based identification involves concerns about privacy and security related to obtaining colour images of individuals operating in restricted workplaces.

On the other hand, there is a growing interest in depth-based and skeleton-based approaches. Indeed, this information is robust to variations of illumination, scale and rotation [8]. Depth-based identification methods aim to create human signature from depth images or videos in the absence of RGB information [9]. While, in skeleton-based identification a small number of joint positions can effectively represent human motion. Barbosa et al. [10] proposed a person signature that exploits skeleton-based features while exploiting soft-biometric features using a set of ratios of joint distances. Similarly, the study of Murano et al. [11] proposed skeletal tracker to determine joints as key points. They extract 2D and 3D descriptors in order to compute signatures of people. By comparing signatures of each target in the test frame with those in training frames, the best match is selected as a result. Those approaches differ depending on the required input data, feature quality and selection, or the need for a training dataset. The basic principle that skeleton-based identification approaches share is finding a skeleton-based person signature that can be unique to each individual.

Some proposed skeleton-based person signatures are:

- Euclidean distance between floor and head
- Ratio between torso and legs
- Height estimate
- Euclidean distance between floor and neck
- Euclidean distance between neck and left shoulder
- Euclidean distance between neck and right shoulder
- Euclidean distance between torso centre and right shoulder
- Geodesic distance between torso centre and left shoulder
- Geodesic distance between torso centre and left hip
- Geodesic distance between torso centre and right hip

Despite the fact that the skeleton tracking of the Kinect SDK is giving natively a body ID to different users in the scene, this body ID is not always consistent over the tracking sequence. The body ID can change when users are overlapping (full body occlusions) or when a user exits the view. Although, performing multiple view skeleton tracking can help retrieving consistent body ID per user along a whole sequence, we investigated different techniques to improve skeleton identification in our single camera IPS.

We developed an identification algorithm using skeleton joints data based on the specific geometrical configuration found in interventional radiology rooms. In the case of interventional radiology, the algorithm makes use of skeleton tracking to correlate the relative position of monitored workers to the camera location. In fact, during our tests we observed that the main operator (the doctor) is usually working in a specific space region on the patient side, while the first assistant is positioned close to the main operator but in a separate region compared to the doctor’ one. Overlapping between these two regions is unlikely when the x-ray beam is on. After each procedure, histories of different body joints of different users can be clustered per user. Hence, the skeleton sequences are modelled as trajectories on 2D plans. This helps identifying monitored users based on their first known geometrical configuration. Skeleton-based person signature can also be used in suitable scenarios. For examples, worker’s height can be used as complementary information that helps to identify different users when applicable. Giving the fact that in interventional radiology workplaces we see only the upper part of the body, it is difficult to rely on a single skeleton-based person signature to identify different users, for example, using the Euclidean distance between feet and neck. Thus, different techniques can be used for different geometrical configurations and for different body size of monitored workers. For now, this procedure is done off-line after the procedure is finished.
In neutron workplaces, RGB-based appearance features could be used to identify the monitored workers whenever they do not have to use PPE equipment that cover or partially cover the face and whenever there are no privacy issues. This is not implemented in PODIUM at this moment. Table 1.2 summarizes the different options for personal identification in PODIUM applications.

Table 1.2. Personal identification methodology when using a 1 single Kinect.

<table>
<thead>
<tr>
<th>Method</th>
<th>Workplace</th>
<th>Requirement</th>
</tr>
</thead>
</table>
| RGB-based appearance Facial recognition | Neutron workplaces where workers do not use masks or glasses | - Face frontal view  
- Good illumination |
| Single-View Skeleton-based      | Interventional Radiology   | - Distinctive geometrical configuration |
| Skeleton-based person signature | Interventional Radiology   | - Distinctive feature among tracked users |
| Multi-view Skeleton-based ID    | Neutron workplaces Interventional Radiology | - Multiple cameras |

III.5 Workflow for setting and starting acquisition with the single sensor PODIUM IPS
A manual is available with the instructions for setting and starting acquisition with the PODIUM 1 camera IPS.

IV. Multi-user IPS with multi-view approach
Because of the occlusions and Field-of-View (FOV) limitations of the single Kinect IPS, a second tracking approach based on a multi camera solution is also proposed. We have developed a software to acquire the skeleton data from different view points so that the identification is correctly performed thanks to the data fusion from different sensors. At present, the software is a beta version. Prior to the development of the software for multi-view approach, existing literature was reviewed to explore several approaches. The most reliable way is to use marker-based motion capture systems [12]. These systems show great results in terms of accuracy (normally less than 1mm), but they are very expensive and require the users to wear many markers. However, in PODIUM, we aimed at finding a marker-less solution and thus this approach was discarded. Now, two possibilities can be considered about skeleton obtention. The first possibility is to use the skeletons provided by Microsoft Kinect SDK. The second possibility is to use OpenPTrack [14]. In this software they compute each single view by using convolutional neural networks (CNNs) for 2D pose estimation (as they do in OpenPose [13]) and extending the resulting skeletons to 3D by means of the sensor depth. OpenPTrack would require the use of GPU and the payment of a license (OpenPose) making the solution more complex and more expensive. Therefore, we discarded the second option, within PODIUM, and we decided to proceed developing a software that performs the body estimation using the skeletal data coming from individual Kinect sensors (using the Microsoft Kinect SDK) connected through a network.

IV.1 Architecture: hardware needs
The proposed multi-user IPS with multi-view approach is based on the use of multiple Kinect sensors. Within PODIUM, the solution has been developed for two sensors but it could be easily adapted for more sensors. It requires one computer for each sensor due to the restrictions of the SDK 2.0 provided by Microsoft. Thus,
in our case, we used two separate computers and an adapted software consisting of two Windows Presentation Foundation (WPF) applications developed in C#, one for the SLAVES or CLIENTS and the other for the master (or SERVER).

The client handles the connection with a unique KINECT sensor. Each KINECT camera needs a PC to collect the skeletons data and send them to the SERVER or MASTER node. This configuration implies that the skeletons’ IDs assigned to skeletons are different in each client and that their joints are referred to different camera positions. Thus a double calibration is needed (see paragraph IV.2). The server handles the connection of the different clients. Its main functions are to perform the fusion of the skeleton data coming from different clients; to carry out the calibration between cameras and the calibration with respect to the world and to send the final recording data for the dose calculation. It can work in Local or Web mode through the PODIUM application (see WP3).

Columns 1 and 2 in Figure 1.8 provide the views from the clients: labels 1 and 2 represent KINECT 0 and KINECT 1, respectively. Columns 3, 4 and 5 (label 6) provide the views from the master. In label 3 we can see the RGB images coming from individual cameras and in label 4 the corresponding depth image and skeleton. In label 5 we can see some data about how many skeletons are identified by each camera and its position, as well as, several buttons to control the program. In label 7 we can see a 3D plot of the fused data and in label 8, the number of fused skeletons and its position.

When using two cameras, one computer runs both the master node and one of the clients that it is attached to the first KINECT. The second computer runs the second client, controlling the second KINECT. Computers communicate with each other thanks to a connection based on TCP-IP protocol. The clients do not send the RGB and depth frames to the master node automatically since this transfer demands a high bandwidth and
it would reduce the frequency of skeleton data. However, this information can be sent under request of the master at any time. In general, they are required in the calibration process and when defining the final set-up in a workplace. There are two alternatives for connecting the computers controlling the Kinects: connecting directly both computers with an ethernet cable (this configuration is the one tested in WP4) or connecting both computers to the same LAN.

IV.2 Calibration of the two-KINECT IPS

The calibration of the system consists of two steps. First of all, the cameras that belong to the network should be calibrated with each other, i.e. finding the geometrical transformation between the multiple cameras. The second process consists in getting the position of one of the cameras with respect to the world applying a similar method as described in paragraph III.2.

Regarding the calibration between cameras, the objective is to refer the skeletons’ data coming from different cameras to the position of the master camera (common reference frame). The implemented method uses the head positions of one person as calibration points to compute the transformation matrix between cameras. There must be just one person in front of the cameras, and he/she must be visible by all of them. Five different positions are used to calibrate with high accuracy but three are enough. The calibration interface indicates when the user must move to the next position with a message and an acoustic signal. Once this is finished, we run the application based on the algorithm presented in [15] to find the optimal rotation and translation (6 degrees of freedom) between two sets of 3D points. The procedure is performed automatically following the instructions indicated in the manual.

The world calibration aims to refer the skeletons’ positions to the world reference point placed at the C-Arm isocentre. In order to locate the isocentre, a QR code is used to detect three different positions of the C-Arm in the XY plane. The QR is situated on the image intensifier. Three acquisitions are performed with the master camera: at 0° which defines the Y axis and at a negative and a positive angle (Figure 1.9).

Figure 9: Example of movements of C-Arm to perform the world calibration of the two-camera IPS.

This calibration procedure relies on depth information provided by the master camera and has, in general, less accuracy than other calibration procedures based on the RGB images provided by the camera which have a higher resolution. However, it has several advantages, such as that it does not need to know the focal length of the RGB, the size of the QR is not relevant for the algorithm and the angles at which the C-Arm must be
placed to calibrate are not fixed. Verification of the accuracy in the position is presented in the next paragraph. The system estimates the accuracy of the calibration adjustments and allows to accept or to repeat the calibration procedure.

**IV.3 Two-KINECT IPS Software**

The software consists of two Windows Presentation Foundation (WPF) applications developed in C# language. As described in paragraph IV.1, we need to execute one *master* software and as many *clients*, in separated computers, as cameras are being used. The master software can run in a separate computer or it can share computer with one of the clients. The fusion of the data coming from the multiple cameras is the key feature of this software. The *master* node is in charge of fusing the different information that is receiving from the single-view detectors in the network. One of the common limitations in multi-camera motion capture systems is the need of having synchronized cameras. Moreover, off-the-shelves RGB-D sensors, such as the Microsoft Kinect v2, do not have the possibility to trigger the image acquisition. In order to overcome this limitation, our solution merges the different data streams controlling they belong to the same specified time intervals (few tens of milliseconds), which is enough for our tracking purposes. The two *clients* send skeleton data as soon as they have a new frame available. The server receives this data and updates the corresponding buffer that store the skeleton data of the different KINECT sensors.

Another difficulty is performing the fusion of the data continuously. First, it needs to transform all the skeletons, provided by the multiple KINECTs, to a unique reference frame (using the calibration data). Second, we associate the skeletons that belong to the same person. To do that, we match those skeletons whose heads are near each other, in a distance below than a certain threshold. This produces a list of sets of skeletons. Then, we calculate the weighted average of all the joints of the input skeletons that belong to the same set. This weighted average takes into account the distance to the skeleton from each camera (the further the object is located from the camera, the worse confidence in the Z coordinate) and whether the joint is being tracked or inferred by the corresponding KINECT sensor.

For future improvements of the software, other approaches can be considered. For instance, in [14] they use Kalman filter for the data association algorithm. In [16] they compute and improve the fused skeleton taking into account the constraints of bone-lengths.

**IV.4 Workflow for setting and starting acquisition with the two sensor PODIUM IPS**

A manual is available with the instructions for setting and starting acquisition with the PODIUM 2 camera IPS.

**V. Evaluation of the methods**

**V.1 Tests with the 1 KINECT system**

The IPS presented in the D9.103 deliverable [1] was successfully tested in simple workplaces, and in a catheterization laboratory (Cath-lab) of UZ Brussels (Vrije Universiteit Brussel) (Figure 1.10), Liège University Hospital and Skåne University Hospital in Malmö. In these scenarios, the system showed to be reliable when tracking one person or even two people with few inter or self-occlusion. However, several limitations were identified that compromised its extension to a multi-user IPS, i.e. a system that would be able to correctly identify multiple individuals in the scene.
The main limitations can be enumerated as:

1. The range of the person tracking algorithm is restricted to about 4.5 meters;
2. The Field-Of-View of the Kinect v.2 depth camera is limited to 84 degrees horizontally and 54 degrees vertically;
3. The maximum number of tracked people is limited to six by KINECT;
4. There might be occlusions affecting the view of the tracked workers;
5. There might be a misidentification of the tracked workers;
6. The position of the joint coordinates can show some fluctuations and sporadic outliers.

The first three limitations are due to the intrinsic hardware features of the KINECT v.2, they cannot be solved without changing the tracking sensor. The KINECT sensor can track up to six people. The individuals in the scene should not be occluded with each other or with objects in the scene (e.g. the ceiling shielding during fluoroscopy guided procedures). Otherwise, the system may lose the tracking of this user. However, a correct placement of the KINECT can decrease the risk of occlusions, allowing a clear view of the part of the bodies of interest. With respect to misidentification, the current tracking software does not provide an algorithm able to identify individuals on line, but we have developed an off-line process to improve this. The algorithm has been tested in two cases recorded in Saint James’ Hospital (see WP4 section).

As shown in Figure 1.7, the implemented filtering algorithm reduces the jittering. Depth images are sampled with the highest frequency, i.e. 30 Hz, and then filtered to a 1 Hz output (sample rate required for the dose calculation), which allows smoothen jittering and spikes.

**V.2 Tests with the 2 KINECT system**

The two-camera system allows monitoring larger areas and tracking from different perspectives which reduces the occlusion problems. Although this tracking software does not provide an algorithm able to identify individuals, by using different viewpoints the misidentification problem caused by track interruptions due to occlusions from a given viewpoint is eliminated or highly reduced, in particular when the number of
people in the scene is below 6. Successful tests were performed in a CV lab with room dimensions of 5.2 meters length and 3.2 meters wide (area 16.64 m²). Two cameras were placed in two corners of the room at heights of 2 and 2.5 meters, respectively, forming an angle of 45° with respect to the wall and an angle of 90° between each other. This camera configuration allows an easy calibration. Moreover, a table was placed in the middle of the room with a dummy in order to simulate the conditions of the PODIUM requirements. Tests were performed with two individuals moving around and with partial occlusions in one of the cameras. It was verified that even when one of the individuals is totally occluded by the other individual in one of the cameras, the fusion of the data produced an output of two skeletons when the other camera distinguished the two people or the person that was occluded in the first camera.

It was verified that by placing the cameras in a good position, the field of view could be extended. Such an advantage is especially important for large workplaces, such as some neutron facilities.

A second test performed in a real Cat Lab in the Barcelona Hospital in Barcelona, without patient, consisted on doing the IPS calibration and verifying the positions calculated by the 2-camera PODIUM IPS and measured with a laser meter. Differences were below 3.5 cm, which is in agreement with the requirements.

**Table 1.3:** Comparison of measured and calculated distances to isocenter of the Spine mid joint of 2 individuals in two different positions (pose 1 and 2) in a Cat Lab in Barcelona Hospital.

<table>
<thead>
<tr>
<th>Pose</th>
<th>“Real” coordinates</th>
<th>Person 1 (SpineMid height = 11 cm)</th>
<th>Difference coordinate (calc - real) (cm)</th>
<th>“Real” distance to isocentre (cm)</th>
<th>Calculated distance to isocentre (cm)</th>
<th>Difference distance (calc - real) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X (cm)</td>
<td>-60</td>
<td>60</td>
<td>0</td>
<td>61.0</td>
<td>61.3</td>
</tr>
<tr>
<td></td>
<td>Y (cm)</td>
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<td>12</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z (cm)</td>
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<td>-4</td>
<td>-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X (cm)</td>
<td>-60</td>
<td>55</td>
<td>5</td>
<td>134.6</td>
<td>131.2</td>
</tr>
<tr>
<td></td>
<td>Y (cm)</td>
<td>11</td>
<td>16</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z (cm)</td>
<td>120</td>
<td>118</td>
<td>-2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pose</th>
<th>“Real” coordinates</th>
<th>Person 2 (SpineMid height = 0 cm)</th>
<th>Difference coordinate (calc - real) (cm)</th>
<th>“Real” distance to isocentre (cm)</th>
<th>Calculated distance to isocentre (cm)</th>
<th>Difference distance (calc - real) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X (cm)</td>
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<td>50</td>
<td>2</td>
<td>60.0</td>
<td>58.1</td>
</tr>
<tr>
<td></td>
<td>Y (cm)</td>
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<td>-1</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z (cm)</td>
<td>0</td>
<td>-4</td>
<td>-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X (cm)</td>
<td>-60</td>
<td>56</td>
<td>4</td>
<td>134.2</td>
<td>130.6</td>
</tr>
<tr>
<td></td>
<td>Y (cm)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z (cm)</td>
<td>120</td>
<td>118</td>
<td>-2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One real case (Case 7 Malmö) was monitored with the 2 cameras. The results are described in section WP4. It was a simple case because only 2 people were present during the procedure. There was only one short misidentification that was easily solved off-line.

**IV. Conclusions Task 1.1**

We have set up two indoor position systems (IPS) to track monitored people. The first system is based on the
use of a Kinect 2.0 depth sensor camera with an adapted software. Mainly the new proposal reduces jittering by incorporating a filtering algorithm based on the Holt Double exponential method, and improves the identification of workers by introducing several specific methodologies, depending on the workplace. In interventional radiology, at the moment an algorithm using skeleton joints data is applied. This one Kinect system has been selected to be used in most tests within WP4 and WP5, because of its ease of use and installation.

The second system is a two-camera solution based on the use of two Kinect 2.0 depth sensor cameras and an adapted software which is capable to fuse the images of the two cameras and thus reduce occlusion problems and increase the field of view of the cameras. The main drawback is that this solution is more expensive since it needs two computers and two cameras.

Both systems are ready for the purpose of the feasibility study but they do not allow the tracking of some objects such as the ceiling shielding or the C-arm movement, which is, sometimes, needed for the dose calculations.
Task 1.2 Geometry input and radiation field mapping

The objective of the PODIUM project is to develop a user-friendly online application to calculate workers’ doses in real time. Instead of measuring individual doses with a physical dosemeter, doses will be calculated. This will be done by using a combination of (i) monitoring of the position of workers in real time and (ii) the simulation of the spatial radiation field, including its energy and angular distribution.

For this methodology, the geometry of the workplace is important since the accuracy of the position monitoring system of the workers will depend on how the system is implemented in each specific workplace; in particular, the placement of the tracking sensors is of great importance. In addition, some of the simulation modules would need a description of the workplaces (dimensions, construction materials...). This workplace description can be done once before the work starts, but it might need to be repeated if relevant elements of the workplace (like the shielding) are subject to change. Another key aspect is the definition of the radiation field. To be able to simulate the staff doses many different parameters that allow characterizing its spatial, angular and energy distribution should be collected. The application of the proposed methodology will be done in two fields that could most benefit of the advantages of it: interventional radiology and workplaces with mixed neutron/photon fields.

I. Workplace geometry

I.1 Interventional radiology workplaces

Interventional radiology and image-guided treatments are areas of the medical sector that could benefit from applying the PODIUM online dosimetry system. In these fields of application, it is foreseen to provide fast dose calculations by using two approaches. The first approach will use a library of pre-calculated dose conversion coefficients, while the second one will be based on the use of fast MC simulations with the MC-GPU code and accelerated calculations with standard codes such as PENELOPE.

The full description of the workplace geometry involves considering several elements present in the operating rooms, since the radiation field that reaches the worker position is mainly composed by scattered radiation produced when the radiation beam generated by the X-ray equipment impinges on the patient’s body.

Among these elements, the characteristics of the X-ray equipment installed in an operating room (X-ray tube, patient table, table shields...) could be considered as part of the workplace description, but in an interventional radiology procedure the operating conditions of this equipment will vary many times during the procedure. For instance, in a typical procedure the same X-ray tube will operate with different kilovoltages and added filtration, and the movable shields will be located at different places. This is why the geometrical description of all of these elements will be included in section II. Radiation Field Mapping devoted on how to characterize the radiation field. In this section only the static elements of the room (walls, ceiling, shelves...) are considered for the workplace geometry definition in an interventional radiology room, since they will affect the placement of the tracking sensors. On the other hand, the materials and dimensions of the room walls have a very little impact on the staff doses and are not going to be included in the MC simulations.
I.1.1 Modelling the operating room
The studied medical procedures are carried out in operating rooms that could have variable dimensions depending on the specific site. The proposed method to model the operating room is to use Structure sensors (Occipital Inc.), i.e., a 3D camera attached on an iPad. The camera uses the RAM-memory to create a 3D mesh of the filmed geometry. The created 3D mesh environment was generated using the app Canvas. The 3D mesh is then post-processed by the additional “Scan To CAD” service in the Canvas app, which converts the generated 3D mesh into an editable CAD file. This file could be used to easily visualize the geometry of the workplace with standard computer-aided design tools such as AutoCAD, and to define the relative positions of the most relevant elements in the room such as C-Arm, bed and shields.

I.1.2 Guidelines on how to set-up the IPS System
The placement of the IPS camera is highly dependent on the features of the IR room where it is installed. For achieving an optimal tracking accuracy, the IPS camera should be placed following a series of ideal criteria, which are described in this paragraph. However, in some cases it could become necessary to compromise some criteria to reduce both the intrusiveness and the possibility of obstructions. The first priority in the placement must be the discreteness of the IPS, i.e. we must assure that the work of the staff is not hindered during the course of any procedure. All the components of the IPS, including the Kinect, the cables and the acquisition PC controlling the IPS, must be placed safely and out of highly trafficked areas. This applies not only to the areas where doctor and nurses walk, but also to the areas where the C-Arm can be moved. Especially in the case of ceiling mounted C-Arms, it is necessary to take into account of the lateral excursion of the device when it is moved along its mounting rail. Assuming that these requirements are met, the first condition for an optimal positioning is that the Kinect should have a front facing view of the staff. With a front facing view, the IPS will deliver the most accurate tracking of chest, head, and of both arms and both hands. To ensure that the tracking is continuous even when the doctor and the medical staff move around the patient, the Field Of View (FOV) must allow for coverage of a sufficiently large area (5-10 m²) surrounding the patient bed.

Considering the horizontal and vertical apertures of the RGB and depth sensors of the Kinect v.2, the ideal position should allow for a final distance between the Kinect and the doctor of about 2 to 4 meters. A distance of about 2.5/3 meters will deliver the highest tracking accuracy. Considering this constraint, the distance components along the longitudinal, lateral and vertical axes needs to be adjusted so that they respect some additional conditions. The vertical distance depends mostly on the height of the Kinect, and it has an obvious implication on the vertical inclination of the camera. The larger the vertical distance, the more downwards the Kinect will have to be rotated, so that the FOV reaches the doctor height. However, due to the inner limitation of the Kinect v.2 recognition algorithm, hard rotations about the horizontal axis (tilt angle) could lead to inaccuracies in the estimation of the joint’s position. Above 25°, there is a high chance that bodies will not be recognized at all. In practical terms, the camera should not be placed above 2.5 meters of height. Similarly, also the horizontal rotation of the camera should not be too high. Hard rotations about the vertical axis of the camera can compromise the view of the doctor. The higher the horizontal rotation, the more lateral the view turns out to be. Lateral views can lead to self-occlusions, i.e. one side of the doctor’s body hides the other side from the camera. In such cases, the Kinect recognition algorithm will try to infer the most probable position of the hidden joints. However, the joint inference algorithm can lead to negative effects on both precision and accuracy, and it can cause high frequency jittering to the hidden hand joint. Furthermore, high horizontal rotation angles will lead to difficulties in the calibration of the IPS. For calibrating our IPS we make use of some reference patterns (checkered boards) that are placed on the room.
walls. The patterns should lie perpendicularly to the camera view to deliver the best accuracy in the calibration. Ideally, to reduce the chance of self-occlusions and to ease the calibration process, the horizontal rotation angle should lie in the range of (-20°, +20°).

![Diagram showing potential Kinect locations within the Malmo test room.](image)

**Figure 1.11:** Potential Kinect locations within the Malmo test room. The most ideal positions are shown in green, while less favourable ones are indicated in orange and red.

Figure 1.11 shows some possible locations for the Kinect. The room geometry is taken from the Malmo Hospital test room number 105 (serving as reference in PODIUM), which has a ceiling mounted C-Arm from Siemens. In this figure, 7 possible locations are shown. The green colour code indicates the locations corresponding to the most ideal positions, while the red indicates the least favourable ones. The red locations would either deliver less accurate tracking data (increasing errors of about 1-2 cm), lead to frequent occlusions, or require a more complex calibration. Nevertheless, all these positions could be used in case the room geometry does not allow for placing the Kinect in the more ideal locations. To summarize:

1) Among all, locations 1 and 2 are the worst. Besides the hard angles (vertical and horizontal) and the high distances to the doctor, these positions are likely to lead partial occlusions when the C-Arm is rotated around the patient body. In this sense, position 5 is already a better option, but it can also lead to partial body occlusions because of the image monitor. However, in this case the camera is far from the monitored area, thus, reducing the useful tracking range and the accuracy of the depth measurement.  

2) In principle, locations 6 and 7 deliver the best combinations of distances, FOV, rotation angles and occlusions risk-free. With such positions, in fact, the distances are maintained within 2 to 3 meters and the risk of self-occlusions and occlusions with objects is very low. However, the implementation of these setups presents some difficulties, reason for which we have not been able yet to place the Kinect in the Malmo test room. In the case of location 6, the problem is that the calibration will be invalidated when the doctor moves the monitor. This issue could be solved by means of an automatic calibration software re-calculating the transformation matrices when a change of position is detected. Within WP1, we will try to study the feasibility of developing an automated calibration software. On the other hand, by adopting the setup number 7 we would solve the issue of the calibration by means of a fixed holder hanging from the ceiling. In this case, we would have to leave an opportune clearance space between the C-Arm and the mounting rack, so that the camera will never interfere with the movements of the C-
Arm. Therefore, in case the automatic calibration software reveals to be too difficult to be implemented for the setup number 6, we will consider the use of a fixed holder.

3) Overall, the locations 3 and 4 are the easiest to implement. The Kinect is far enough from the C-Arm, and the central position allows a frontal view of the doctor. So, even if the distances Kinect-doctor are relatively large, these Kinect locations still lead to a good tracking accuracy. The most concerning issues for these setups are the high tilt angle (especially in position 3, which can lead to a complex calibration) and to the risk of occlusions when the C-Arm is rotated towards the centre of the bed.

I.2 Mixed neutron-gamma workplace fields
The PODIUM system will be used in workplace fields that contain neutrons. However, due to the physical nature of neutron generation and of neutron-matter interactions, such fields will inevitably also contain photons. So, the system must in fact be suitable for dosimetry in mixed neutron-gamma fields.

Example scenarios where such fields can exist include, but need not be limited to:

a. nuclear power stations and their associated support facilities, such as fuel processing, transport, and de-commissioning industries;
b. accelerator facilities that have beam types and energies capable of producing neutrons as either primary or generated particles, such as might occur within high-energy research accelerators or around medical accelerators;
c. engineering applications that utilize neutrons, such as for geological analyses of samples.

Within the scope of the PODIUM project, suitability of the system in the above types of field will be tested at two sites. The first is within the Radiation Metrology laboratory facility at PHE’s Centre for Radiation, Chemical and Environmental Hazards (CRCE) in Chilton, UK. At this site, the low-scatter environment routinely used to perform Secondary Standards certified exposures to a $^{241}$Am-Be source has been modified by the inclusion of water tanks to produce a location- and angle-dependent field that has been shown to be similar in energy distribution to the types of workplace fields that can exist at a nuclear power station. The second is within a nuclear facility hosted at the SCK•CEN site in Mol, Belgium. At this facility a transport container with spent MOX fuel was placed in a large room. This setup represents a realistic mixed neutron/gamma workplace field in which workers can receive significant neutron dose.

I.2.1 Modelling of the geometry
The geometry of mixed neutron/photon workplace fields needs to include objects/materials that emit radiation or that can significantly influence the staff doses. Furthermore, different objects/materials in the workplace can affect the radiation field by shielding or scattering. It is therefore necessary to assess which objects/materials significantly affect the radiation field. The most important objects/materials need then to be included in the workplace geometry. For simple geometries this can be done by using simple macro-bodies. For more complex geometries, it might be necessary to use a CAD model. If a CAD model is not yet available it might be generated for instance by using the technique described for interventional radiology workplaces.

In principle, the model of the facility needs to be sufficiently detailed to provide an accurate estimate of the dose rate at every location at which an individual might conceivably be located within it. The transient nature of the field would also need to be considered in environments in which that is relevant, such as fuel storage facilities, for example, where the inventory and spatial positioning of radioactive sources in the area might...
change over time. In practice, the above requirements would be impossible to fulfil completely. However, several overall approaches may be adopted to mitigate against the problems caused by imprecise or incomplete knowledge of the input required for the model, and standard good practice will help to optimize the reliability of the results obtained:

**Simulation code:** The simulation code used to generate the dose rate data can be either deterministic or Monte Carlo, general-purpose or user-specific. The only condition is that it needs to be fit for purpose, and hence able to output accurate data that is reliable for both neutrons and photons. This requirement may be demonstrated via independent testing and benchmarking. It is necessary to run Monte Carlo calculations in coupled neutron-photon mode, with kerma conditions generally assumed such that electron transport may be neglected.

**Modeller:** The accuracy of the dose rate map will clearly depend on the ability of the individual performing the modelling: it is obvious that they must be sufficiently familiar with mathematical modelling techniques to not only be able to construct a reliable model of the facility but also understand the uncertainties and limitations associated with their approach. This would include an awareness of parameter-sensitivity analyses, and an ability to determine which factors (e.g. objects, materials, physical parameters etc.) within their facility would be most key to obtaining accurate results.

**Parameter variation:** Even if a modeller could reproduce the geometry of their room with apparent high fidelity, there is still the possibility that ‘hidden’ aspects within it could impact dose rates. Examples here could be the unknown presence of neutron absorbing material behind a wall panel, which could significantly affect scatter, or imprecise knowledge of the material compositions or densities that they input into the model. It is therefore necessary to perform parameter sensitivity analyses of the modelled environment, to ascertain which factors are most and least significant. Furthermore, it is then necessary to benchmark the results against measured data. Estimates of ambient dose equivalent rates are suggested for this, because survey instruments are typically readily available within workplace fields. Given the energy-dependence of response of typical survey instruments, only broad confirmation may be possible.

**Time dependencies:** It is possible that the geometry of the modelled room may be time-dependent, leading to a time-dependent dose rate map. It may therefore be necessary to produce a set of ‘contingency’ dose-rate maps for a given environment, each for a different anticipated configuration of objects within it, with the choice of which map is most appropriate to use made in real-time. The use of installed area monitoring equipment could also be employed to provide real-time dose assessments and correction factors.

The above headings provide discussion on the general approach to modelling the geometry of a given neutron facility of interest. To illustrate the overall methodology, however, it is instructive to consider case studies that relates to the modelling of a real facility.

**II. PHE Neutron Facility**

An image of the PHE neutron facility is shown in Figure 1.11. Cross-sectional and plan views of the PHE neutron facility are shown in Figure 1.12. The figure is schematic, being generated as output from a Monte Carlo model using the VISED package of MCNP. The laboratory is essentially a rectangular room, approximately 8 m long, 5 m wide, and 2.5 m high, with the source and exposure platform positioned on the
central long-axis. When not in use, the $^{241}$Am-Be source is stored below ground, but is raised to a height of ~1.25 m above the floor during exposures.

![Image](image_url)

**Figure 1.11:** The PHE Neutron Laboratory in routine use. The $^{241}$Am-Be source is contained within a steel tube, itself partially encased within a lead shield (painted yellow). A moveable platform allows objects to be placed as different distances (and heights) along a central axis away from the source.

To build the model, measurements were made of the physical dimensions of every aspect of relevance within the real laboratory (Figure 1.11). It is evident that aspects of the facility that were considered unlikely to affect the dose at a given location have not been included in the model; typical examples of this are small objects that may be judged not to induce significant neutron scatter, such as wall-fixtures, control panels, a monitor screen, and the wooden desk placed against the wall. With all dimensions recorded, a scale diagram was produced that could subsequently be translated into the MCNP model.
Figure 1.12a: Cross-sectional view of the PHE Neutron Laboratory in ‘normal use’. The figure is truncated in the left-right direction: the actual laboratory is ~8m long (Y-axis) and ~2.5m high (Z-axis).

Figure 1.12b: Cross-sectional view of the PHE Neutron Laboratory including water tanks adjacent to the source.

Figure 1.12c: Plan view of the PHE Neutron Laboratory. The water tanks are shown in blue, with the $^{241}$Am-Be source (red) positioned adjacently. The walls (yellow) incorporate wood panels placed in front of Premadex neutron-absorbing material. The laboratory is ~8m long (Y-axis) and ~5m wide (X-axis).

Once the spatial arrangements of objects had been defined, these shapes were ‘filled’ with the correct materials within the MCNP input file, in accordance with the physical objects present in the actual laboratory. Of course, the accuracy of the model will depend on the accuracy with which the materials can be defined, which may be complicated if the precise chemical and isotopic composition of a given object in a geometry is unknown. In such cases, best guesses and compromises would be inevitable. For the PHE laboratory, however, most of the materials used in its construction can be assumed to be fairly commonplace, such as
the aluminium, stainless steel, lead, polymethyl methacrylate, wood and Premadex used to build the facility, and the water of the moderator. Typically, it was fairly easy to obtain physical density data from reliable and referenceable online sources for most common materials. The chemical composition of common materials is also relatively easy to obtain.

Once the shapes comprising the physical objects have been ‘filled’ with materials within the MCNP model, the specification of the geometry is essentially complete. However, the source term needs also to be defined within the model. For most workplace facilities where neutrons may be present, such as within the nuclear sector, the neutrons originate from a radioactive source of physical dimensions, density and material composition. Thus, source and geometry are effectively ‘coupled’ within Monte Carlo models containing neutrons, so the physical parameters of the source need to be incorporated into the specification of the input geometry. For the PHE source, this was relatively easy: the neutrons are emitted from a small cylinder of aluminium (~few cm³), inside of which the $^{241}$Am-Be is distributed

In addition to the physical specifications of the source, the energy distribution of the emitted neutrons needs to be defined within the model. Again, this is a relatively easy for the PHE $^{241}$Am-Be source, which is a well-defined calibration source that emits according to ISO 8529 [17] specifications. Moreover, MCNP normalizes all output results to ‘per-source-particle’. In order to link that output to the real world, the activity of the source needs also to be considered, such that a multiplication factor may be introduced. As before, this is relatively easy for the PHE source, which is well benchmarked and is calibrated to secondary standards criteria.

Similarly to the specification of the material data, the accuracy of the model will depend on the accuracy with which the source term can be defined. For the PHE neutron facility model, the accuracy may therefore be assumed fairly high: the energy distribution of emitted neutrons and the composition of the source pellet are both well-known and well-characterized, with the dose rates at the point of test typically determined to better than 10 % uncertainty. In a general workplace environment, however, this may not be the case: the compositions and contents of fuel flasks, for example, may be known only to a limited extent, and the presence of short-lived radionuclides could lead to a transient emission characteristic. The extent to which ignorance of the source term and its immediate environment will impact the dose rate at a given location will obviously vary on a case-by-case basis, but could be significant and again emphasizes the need for corroborative measurements and a cautionary approach to the modelling. This type of uncertainty has been investigated by applying the PODIUM approach to the SCK•CEN workplace field.

### III. SCK•CEN neutron workplace field

![Figure 1.13: Picture and MCNP model of the SCK•CEN neutron workplace field](image-url)
Most of the considerations mentioned already for the PHE field were also applicable for the SCK•CEN neutron workplace field with the transport container with MOX fuel rods. The geometry of the room and the relevant objects was relatively simple to model. The concrete floor, the lead slab in the floor, the concrete wall, the lead transport container and the MOX fuel rods were modeled by measuring the relevant dimensions, making a schematic drawing and modeling the geometry directly in the MCNP input file by using macrobodies (see Figure 1.13).

Modeling of the source was the most challenging part. In contrast to the PHE field, here the source was not well characterized. The history of the fuel rods, literature study and benchmarking of the simulations with measurements were required to model the source realistically. This will be discussed in more detail in this report in the chapter on WP5.

I.2.2 Guidelines on how to set-up the IPS System

The main difficulties for mixed neutron/photon workplace fields arise from the fact that such workplaces can be very large and a lot of workers can be present in one workplace. Therefore, often the use of 2 or even more tracking cameras will be required and the tracking algorithms need to be able to track all the workers present in the workplace. Inevitably, use of the tracking cameras within a facility will vary on a case-by-case basis, with their number, locations and orientations fully dependent on the geography of the room and the objects within it, noting that these latter may potentially be variable. The objective would be for the cameras to be able to determine, at all times and for all anticipated configurations of the geography, the position and orientation of each individual within it.

For the case study of the PHE Neutron laboratory, choosing the number and positioning of cameras may be relatively straightforward. Occlusions of individuals within the field-of-view can only be caused by the central components, or by the presence of other workers (if any) in the laboratory. If this latter of these may be neglected, use of two tracking cameras may therefore be sufficient, because the only likely occlusion of that individual is by the moderating tanks. The natural positioning of the two cameras would be in diagonally opposite corners of the room, assuming that each camera can track to a range of at least “6 m and has a field of view of at least 90°. The door to the laboratory is at the bottom-right of Figure 1.12c, so the obvious locations of the cameras would therefore be in the bottom-left and top-right corners of Figure 1.12c. Due to its similarly open ‘geometry’, an analogous Kinect set-up might be expected for the SCK-CEN facility (Figure 1.13).

A sufficiently accurate characterization of the radiation field in the workplace is crucial for a correct estimate of staff doses by simulation. Many parameters must be collected for allowing to characterizing spatial, angular and energy distributions of the radiation field. Neutron fields are always mixed with photon radiation, however, in the framework of this project we will focus on the calculation of the neutron contribution of the mixed fields. In interventional radiology, the radiation field changes several times during a procedure of several hours. Thus, for this application a continuous calculation of the radiation field is required, whilst radiation fields for mixed gamma-neutron workplaces are not much time dependent. But even in this case the radiation field can vary, therefore, it might be necessary to have an external dosemeter to scale the radiation field map proportional to this external dosemeter reading and use this as correction on temporal changes.
II.1 Interventional radiology workplaces

II.1.1 Radiation field: required information and data sources

In interventional radiology workplaces it is foreseen to provide fast dose calculations by using two approaches. The first approach will use a library of pre-calculated conversion coefficients, while the second one will be based on the use of fast MC simulations with the MC-GPU code and other accelerated calculations with standard codes such as PENELOE. The radiation field lookup table is developed within WP1 task 1.2, while the creation of the sets of dose conversion coefficients is part of WP2 of PODIUM. The two tables will be integrated in a dedicated software (developed in WP3), named IPP_SE, which is run remotely by the web application. In the second approach, the radiation field at the position of the monitored worker is calculated “live” by the MC programme used in the dose calculation for each irradiation event.

Required information

The scattered radiation field should be calculated with clinic and patient specific data, but for both foreseen approaches the same basic information is needed. Some of these data correspond to the physical configuration of the X-ray tube and could be considered as fixed values for a specific room, and gathered during the setting-up of the dosimetry application in the facility, see Table 1.4.

**Table 1.4.** Fixed Information related to the generation of the X-ray beam and expected data source.

<table>
<thead>
<tr>
<th>Required information</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X-ray tube characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Anode (angle and material) of the X-ray tube</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Inherent filtration of the X-ray tube (thickness and material)</td>
<td></td>
</tr>
<tr>
<td><strong>Examination room components</strong></td>
<td></td>
</tr>
<tr>
<td>C-arm radius of the stand (i.e. isocenter location)</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Image intensifier components</td>
<td></td>
</tr>
<tr>
<td>Patient table and mattress characteristics (material, thickness) or attenuation data</td>
<td>Manufacturer or Experimental Measurements</td>
</tr>
<tr>
<td>Characteristics of movable protective elements (table shields, ceiling-mounted or wall-mounted shields…)</td>
<td>Manufacturer</td>
</tr>
</tbody>
</table>

However, there are patient specific data that have to be retrieved in real-time or at a minimum be available at the end of a procedure:
- Anatomy of the patient modelled by using anthropomorphic phantoms, as the main scattering body. The thickness of the exposed body, the main parameter, could be predicted knowing the weight, length, sex and age of the patient. This information should be introduced by the operator in the DCA.
- Anatomical region examined (chest, abdomen, ...), procedure type.
- For each projection/irradiation event:
  o Date/time it started, duration.
  o Focal spot position.
  o Shape and size of the radiation field.
  o Source to image intensifier distance.
  o Source rotation angles.
  o kVp (kV).
  o Added filtration.
  o Position of the reference point.
  o Dose at the reference point, for normalization purposes.
  o Position of movable protective elements (table shields, ceiling-mounted or wall-mounted shields...).
  o Patient’s table position (x,y,z) in (cm).

Data sources
The acquisition modality acquires the images, generate different reports, temporally store and send them to the Picture and Archiving System (PACS) following the DICOM protocol. There are different data sources generated by the acquisition modality:

- Patient images. There is some information included in the DICOM-header files, but not all parameters needed.
- Radiation Dose Structured Report (RDSR). The document contains information arranged in a branching manner on different hierarchical levels that are linked to one another (XML structure).
- Modality-performed procedure steps (MPPS) report. Generated by the modality, can contain information about the examination, but there is a high variability of contents.
- Abbreviated Reports. There is some information included in the DICOM-header files, but not all parameters needed.

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. Figure 1.14 gives a schematic overview of data sources that could contain important data.
Commercially available dose management systems are based on the Radiation Dose structured Report and offer the possibility to export it in Excel format. However, the available system will be different for each hospital, and in particular, at Skåne University Hospital the DoseTrack system from Sectra is available, but at Saint James Hospital at the beginning of the project there was no dose management system available, and nearly at the end they could use DoseWise system. Consequently, for the PODIUM project the preferred data source will be the RDSR.

Finally, at Skåne University Hospital the RDSR in DICOM format can be directly obtained from the workstation of Siemens acquisition modalities whilst at Saint James Hospital, also from Siemens modalities, the data extraction was only possible in Excel format by using an application provided by the vendor. In all cases the RDSR-files are available from the workstation only after each treatment finalizes. For these reasons, the PODIUM dosimetry calculation application (DCA) has been developed (in WP3) to deal with the RDSR formats available at Skåne University Hospital and Saint James Hospital, where the PODIUM application will be tested (WP4). However, the DCA is structured so that it could be easily adapted to another RDSR output and also it could correctly deal with real-time information of the irradiation event (during the procedure).

In addition, it should be pointed out that the RDSR does not always contain all the required information for the dose calculation and, that, RDSRs from different vendors do not exactly match. Each vendor follows its own DICOM Conformance Statement. However, different x-ray machines from the same vendor comply with the same format (i.e. contain the same information data). RDSR files from Skåne University Hospital and Saint James Hospital (from Siemens systems as has been mentioned before) have been revised to identify the available information, the information that can be determined even if it is not included in the RDSR, and the assumptions that can be made for the missing information. Table 1.5 summarizes the required information, identifies if it is directly available or, if needed, and not available, the proposed strategy to derive it. In addition, although it is not initially foreseen to use Philips systems in PODIUM, some RDSR files from Philips modalities were also studied.
Table 1.5. Specific patient procedure and expected data source.

<table>
<thead>
<tr>
<th>Required information</th>
<th>Available through the RDSR</th>
<th>Alternative method to derive it</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procedure type</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Date/time started</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Duration (ms)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Focal spot position (related to operator coordinates)</td>
<td>Not available</td>
<td>Indoor Positioning System</td>
</tr>
<tr>
<td>Size of the radiation field</td>
<td>Not available in Siemens systems, available for Philips</td>
<td>When missing, the value will be calculated by using the Dose Area Product, assuming a square field</td>
</tr>
<tr>
<td>Shape of the radiation field (position of the collimators)</td>
<td>Not available in Siemens systems, available for Philips</td>
<td>The field shape will be assumed to be squared</td>
</tr>
<tr>
<td>Source to image intensifier distance</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Source rotation angles (Primary and Secondary angles)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>kVp (kV)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Added filtration</td>
<td>Available for Siemens, not always available for Philips</td>
<td>The value can be gathered from the manufacturer, derived from the applied protocol</td>
</tr>
<tr>
<td>Position of the reference point</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Dose at the reference point (Gy)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Dose area product (Gym²)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Patient’s table position (x,y,z)</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Position of movable protective elements (table shields, ceiling-mounted or wall-mounted shields...)</td>
<td>Not available</td>
<td>Specific positioning system (based on cameras or inertial movement sensors)</td>
</tr>
</tbody>
</table>

It should be commented that the X-ray console time stamp has to be synchronized with other equipment and programs, in particular with IPS output. The position of the table in lateral and longitudinal direction may be set to zero by the operator in order to set reference for an anatomical structure during the treatment. So, this zero position is not standardized and it is likely to vary with each room installation making it unusable as reference. However, for simulation purposes it can be sufficient to know the anatomical region of interest to position the patient’s body.

II.1.2 Radiation field lookup table approach
The first of the two calculation approaches used in PODIUM is based on the creation of lookup tables comprising information of the radiation field and the organ dose conversion coefficients. This approach was established by PODIUM members as an intermediate step towards real-time simulations. This approach could still be useful in those cases where it is not feasible to perform fast simulations, because of the lack of a fast and stable internet connection to connect with the calculation server or because of the lack of high computational power in-situ, which is often the case in hospitals.

The radiation field lookup table includes the data used for characterizing the field in the so-called scatter sphere and ray tracing approach. The data are stored in a series of scatter fluence files corresponding to a fixed set of input source parameters, which include machine parameters (kVp, primary and secondary projections, filtration, focal spot position relatively to the patient body etc.) and types of patient body. Each scatter fluence file contains the energy spectrum of the photon fluence found on a sphere centered in the focal spot of the C-Arm.

The energy distribution of the fluence is computed by means of the MCNPx 2.70 transport code, using the F5
tally with the energy discrimination card DE. For the calculation, the surface of the sphere is approximated with small rectangular faces inscribed in the sphere. Each sphere is segmented in 2592 rectangular faces, i.e. one face every 5 degrees for both polar and azimuthal angles. Furthermore, depending on the distance between the doctor’s body and the focus spot of the C-Arm, different sphere diameters are used. This allows to increase the accuracy of the dose calculation methodology, especially when the range of distances between the doctors body parts and the patient body varies from very close of the primary beam (0.5 m) to 1.5-2 meters far (for example, in case the pedal is used at distance during acquisitions and fluoroscopy moments). In order to reduce the extent of the radiation field lookup table, for the moment the PODIUM dosimetry system makes use of 2 sphere diameters for close-by and farther doctor body joints: 50 and 80 cm. The radiation field lookup table containing the scatter fluence files is integrated in the dedicated software IPP_SE, which is run directly by PODIUM’s web-application. Besides handling the radiation field lookup table, IPP_SE is also used for convoluting relevant parameters for the source definition with the tracking data, and thus to provide the dose calculation based on the dose conversion coefficient lookup table. In the DCC table, the anterior surface of the upper part of the phantom is subdivided in 6 rectangular faces, named Field Panels.

The Field Panels are:

1) Top left/right covering head and neck,
2) Mid left/right covering the chest, and
3) Bottom left/right covering abdomen and pelvis).

In WP2, organ DCCs are calculated by irradiating one field panel per time with a parallel monoenergetic beam of photons impinging with a certain angle θ.

The convolution between machine parameters (defining the radiation field), doctor position and posture is achieved through a ray tracing algorithm included in IPP_SE. The algorithm ‘traces’ rays between the focal spot and the 6 field panels, calculates distances and incidence angles θ between the focal spot and doctor body parts. The convolution links the calculated incidence angles with the corresponding energy distributions taken from the scatter fluence file. This information is then used to pick the correct organ dose conversion coefficient from the respective lookup table, for each field panel. Finally, the intensity of the fluence is corrected by the DAP value (read from the RSDR) and reduced by a rescaling factor (<1) proportional to the distance between the field panel and the focal spot. This fluence rescaling factor is obtained on the basis of our validation and sensitivity studies, and it can be seen as an extension of the inverse square dependency of the intensity of a point source. The development of this algorithm is carried out together with the development of the dose conversion coefficient lookup table, and thus within WP2.

However, the size of the lookup table and thus the total number of scatter fluence files depends on relevant combination of input source parameters, which is assessed by means of a sensitivity study. For the first validation of the PODIUM dosimetry system, it was decided that the total number of scatter fluence files will be limited below the thousand cases. Nevertheless, it will be always possible to increase both the amount of fixed sets of input source parameters and the sphere diameters by means of future software update, should higher accuracy be needed. A sensitivity study has been performed to decide on the criteria to select the simulated sets for PODIUM (see II.1.4).
II.1.3 Radiation field fast Monte Carlo calculation approach

The two fast Monte Carlo approaches used for the dose calculations read input files which are adapted by the PODIUM application (DCA) from the RDSR file. The DCA organizes the radiation source information as it is required by each Monte Carlo programme. Details on the specific data needed are described in WP2 section.

II.1.4 Sensitivity study on parameters of influence

The scattered field that reaches the operator depends on different parameters, but it is expected that some of them will be more critical than others. The knowledge of the impact of these parameters on dose is a key factor to optimize the size of the radiation field lookup table. This analysis is also useful to assess whether the number of simulations in the fast simulation approach can be reduced. In order to study the influence of the different parameters on the operator’s radiation dose, several Monte Carlo simulations of the dose at different positions of interest have been carried out. Simulations were performed with PENELOPE/penEasy code. The ratio operator dose versus the dose at a reference point was calculated.

This ratio is the most interesting quantity since all simulations will be normalized to experimental values by using the dose at the reference point or the dose area product included in the RDSR files. The reference point is a virtual position defined at a specified distance from the isocenter of the C-arm. The air kerma or the dose at this point is calculated by means of the measurement of a DAP-meter located in the housing of the gantry at a fixed distance of the focal spot and using the inverse square law.

The sensitivity study has been carried out taking into account information from the Skåne University Hospital on the most commonly used working conditions. From the results some conclusions can be drawn:

- As regards kVp, without added filtration, the dose is quite dependent on kVp, but it can be described by a linear equation.
- Regarding added filtration and kVp, the most frequent added filtration in the clinic, are 0.9 mm, 0.6 mm and 0.3 mm of Cu. In addition the sensitivity analysis highlights differences within 15% between 0.9 mm and 0.6 mm or between 0.6 mm and 0.3 mm. For this reason, for the moment it was decided that we will simulate 4 cases of added filtration (0 mm, 0.2 mm, 0.3 mm, 0.9 mm) for the creation of the first scatter fluence files in the lookup table.
- Concerning the dependence on field size, as expected, the operator dose shows a linear dependence with the square field size value. Simulating 3 field sizes (15 cm, 20 cm and 30 cm) will allow us to reduce the total number of simulations maintaining accuracy in dose estimation.
- Finally, the dependency of operator dose with primary and secondary angulation was investigated. The results of our analysis show a complex but expected behaviour, which allowed us to reduce the extent of angles to include in the first radiation field lookup table. On the one hand, by simulating 7 primary angles (90RAO, 45RAO, 30RAO, PA, 30LAO, 45LAO, 90LAO), 3 secondary angles (30CAU, 10CAU, 30 CRA) and by using interpolations between these angles, we will be able to provide accurate field characterization for any primary and secondary angles.

In total, this leads to a total number of 1764 configurations, corresponding to 7 energies, 4 thicknesses of added filtration, 3 field sizes, 7 primary angles and 3 secondary angles.

To conclude, the information obtained with this sensitivity study allowed us to define the size of the radiation field lookup table.
II.2 Mixed gamma-neutron workplace fields

II.2.1 Radiation field mapping

The ultimate aim of the PODIUM system is to be able to perform real-time calculations of effective dose for individuals tracked by the Kinect camera. Achieving this by introducing a voxel phantom into a model of a room, and performing Monte Carlo calculations in real-time, is not possible for mixed gamma-neutron fields due to difficulties in applying the correct radiation weighting factor to the doses deposited in the organs. As a result, the method of solution adopted by the PODIUM system is to determine in advance a set of dose rate maps appropriate for the workplace (look-up table approach), and apply those in real-time given the tracked motion of the individual.

Significant vertical dose rate gradients might exist in practical workplace fields, but most of the organs that contribute to effective dose will likely always be between ~1m and ~1.5m from the floor. Nevertheless, data at heights corresponding to a standing and a bended (or sitting person) could also be calculated if required.

For this reason, the approach recommended within PODIUM is to map the dose rate on a horizontal grid located above the floor at the height of ~1.25 m from the floor if no significant vertical dose rate gradient is expected. It is assumed that this approach would provide a reasonable or conservative estimate of doses in the majority of cases. For the simulated workplace field developed at PHE, the $^{241}$Am-Be source is also located at 1.25 m from the floor of the facility. In the case of the other selected workplace, a transport container with spent UO2 or MOX fuel at SCK·CEN Research Centre, a larger height variation is expected because also kneeling persons can be expected and the container is situated on the floor.

The approach to the mapping is to generate dose rate data as a function of location within the room in which the PODIUM system will be installed. The simplest such approach would be a regular 1 m $\times$ 1 m grid of points extending over the whole area, but it may be desirable to increase or decrease this resolution as appropriate, and the grid itself need not be uniform: more points could be clustered in the most dosimetrically relevant regions. As always, choice of the most suitable grid structure would have to be made according to the requirements of the site in question.

With the grid defined, dose rate data would be determined for each point on it. Effective dose depends on the orientation of the individual, so in fact at each point on the grid a family of angle-dependent dose rate data is required. On implementation of the PODIUM system, the position of the centre of the individual and their orientation would be tracked in real time, and this would then be associated with the nearest discrete position and angle for which dose rate data have been mapped. Those data could then be used to derive the dose to the individual for the duration for which they can be considered at that location and orientation. As the individual moves, his/her position and rotation is tracked: eventually it will become closer to one of the other datapoints on the defined grid, which would lead to the selection of a different value from the field map.

Although it is the effective dose to the individual that is ultimately of interest, it is recommended that also the ambient dose equivalent rate map is produced for each site. $H^*(10)$ is preferred for the verification because, in general, neutron survey monitors response is better known.

**Ambient dose equivalent, $H^*(10)$, rate:** The total ambient dose equivalent rate is to be determined at each location of the grid. There are two motivations for this: firstly, it allows the model to be checked against...
confirmatory measurements that can be made in the field using readily available instrumentation, such as hand-held survey instruments; secondly, it supports the use of installed monitors in facilities, which will be important for dose normalization and ongoing renormalization.

One way of obtaining the ambient dose equivalent map may be to define a sphere of air of radius $r$ at each position on the grid, where $r$ is small compared to its distance from any source (e.g. $r \approx 10$ cm, when a $1m \times 1m$ grid is used with its origin at the source). The contribution to $H^*(10)$ from photons at each location may be obtained by determining the fluence-energy distribution through the sphere and convolving that by the energy dependent fluence-to-$H^*(10)$ conversion coefficients provided in ICRU Publication 57 / ICRP Publication 74 [18]. In MCNP, for example, this is readily achieved using a binned $f4:p$ tally in conjunction with $de4$ and $df4$ tally multipliers. The contribution to $H^*(10)$ from neutrons at each location may be obtained similarly, but of course using a $f4:n$ tally, different appropriate $de4$ and $df4$ tally multipliers with different bin structures, and log-log interpolation. Summing the contributions from photons and neutrons provides ambient dose equivalent per source neutron; multiplying the result by the known neutron emission rate of the source leads to an estimate of the absolute value for ambient dose equivalent rate at each location.

If models of neutron survey instruments exist, such as for the GNU device that was developed by PHE, subsidiary calculations can also be performed. Specifically, the device can be placed at selected locations on the grid within the model to provide additional comparisons with measured data. This approach provides two benefits: firstly, it mitigates for the inevitable energy-dependence of response of the instrument; secondly, it mitigates for the inevitable perturbation of the field caused by the bulk of the instrument, relative to the free-in-air calculations performed for the dose map.

**Effective dose, $E$, rate:**

A ‘spectral’ method of determining effective dose indirectly has been developed within PODIUM. The procedure involves calculating the energy and angle distributions of the neutron and photon fields, as well as their magnitudes, at each location on a discrete grid; these data can then be convolved with energy and angle dependent fluence-to-effective dose conversion coefficients, with the two components then summed to provide a map of the total effective dose rate, subsequent to appropriate normalization. Specifically, the overall method is to resolve the anisotropic field at a given location into a discrete spectrum of separate angular components. A schematic of the general approximation approach in a horizontal plane is shown in Figure 1.15, where a $45^\circ$ resolution has been chosen to give eight angle components.

![Figure 1.15](image)

*Figure 1.15: Schematic of the angular deconstruction method in a horizontal plane: the real anisotropic exposure (left) is approximated as the sum of plane-parallel exposures from eight different directions (right).*
For components from a fixed direction, e.g. posterior-anterior (Figure 1.15, bottom-right), it would be natural to apply plane-parallel fluence to effective dose conversion coefficients. However, one limitation here is that plane-parallel data are not provided in ICRP 116 at all angles: instead, only AP (i.e. 0°), PA (i.e. 180°), LLAT (i.e. 270°) and RLAT (i.e. 90°) data are provided (Petoussi-Hens, Bolch et al. 2010). As a result, additional datasets had to be generated within PODIUM WP3 corresponding to exposures at intermediate angles.

In Monte Carlo codes such as MCNP it is non-trivial to estimate the angle distribution of fluence at a point, because of ambiguity in defining a reference direction. To overcome this, adoption of an angle binning structure is required. In turn, this leads to a family of calculations being performed at each location on the grid to generate the angle-dependent effective dose map using the separate angle bins. To illustrate the general approach, consider a Cartesian coordinate system defined such that the \((x,y)\) plane is parallel to the floor, and the \(y\)-axis can be considered an arbitrarily chosen reference direction. Consider also defining a circular region of finite size, with a radius that is small compared to the geometry of the room and grid (e.g. ~10 cm), and such that a reference vector normal to the surface is parallel to the \(y\)-axis; it might be considered that this disc is ‘facing’ along the \(y\)-axis. In fact, by considering both ‘front’ and ‘rear’ surfaces of the disc, it could be described as facing both along and away from the positive \(y\)-axis (+\(y\)).

Consider now an MCNP fluence tally binned according to the angle structure “0° - \(\theta\)° (180-\(\theta\)°), 180°”, relative to the normal to the surface. Within the Monte Carlo code, this would separate the fluence into 3 bins of particles arriving in:

- the cone defined from 0° to 0° (i.e. a cone with an opening half-angle of 0°)
- a hollow cone defined from 0° to (180-\(\theta\)°)
- the cone defined from (180-\(\theta\)°) to 180°

Assuming \(\theta\) is sufficiently small, the first of these angle bins may approximate the fluence of particles incident from the ‘front’, i.e. the component of the decomposed field that is roughly in the -\(y\) direction. If the fluence-energy distribution of these particles is then convolved with appropriate anterior-posterior (AP) fluence-to-effective dose conversion coefficients (via a \(f4:n\) or \(f4:p\) tally in conjunction with their individual \(de4\) and \(df4\) tally multipliers), then an estimate can be derived for the ‘forward’ component of effective dose. That is, if an individual were standing at that location and facing along the positive \(y\)-axis, the approach would provide an estimate of the approximately AP component of their effective dose. Alternatively, if the fluence-energy distribution of these particles were instead convolved with posterior-anterior (PA), left lateral (LLAT), or right lateral (RLAT) conversion coefficients, then estimates would be derived for those components of effective dose for individuals standing at that location and facing along the negative \(y\)-axis, positive \(x\)-axis and negative \(x\)-axis respectively. Furthermore, an analogous process for the cone defined from (180-\(\theta\)°) to 180° would simultaneously provide the components that are complement to those above.

This process may be generalized by rotating the circular region by an angle \(\phi\)°, such that the reference direction becomes an angle of \(\phi\)° to the positive \(y\)-axis, and repeating the procedure. This would provide front and rear contributions to effective dose for individuals facing along and away from this new reference direction, as well as left and right contributions to effective dose for individuals facing along and away from a direction that is 90° to it. Iterating this procedure for a range of \(\phi\) angles from 0° to 360°, and summing the different components for both neutrons and photons from the various directions, allows an estimate of total effective dose to be obtained for any arbitrary direction in which an individual might be facing. Of course, to avoid double counting the opening angles of the various tally cones would have to be such that no two cones overlap.
The above approach will provide a first estimate of the various components of effective dose from exposures predominantly in the horizontal plane (Figure 1.16, left). However, it is still necessary to ensure that the full $4\pi$ solid angle is taken into account to avoid underestimates of the true dose at each location. This necessitates the definition of additional tally cones, with axes orientated in directions other than the horizontal plane, and with the double-counting constraint again enforced such that no two cones overlap. Clearly, the inclusion and structure of these non-horizontal cones will depend strongly on the characteristics of the field, and which angular components of exposure are expected to dominate.

![Figure 1.16](image)

**Figure 1.16.** PODIUM approach to fluence decomposition at each point, showing: (left) 2 vertical cones and their coverage and 4 of the 8 horizontal cones ($\theta = 22.5^\circ$); (right) the tangential $\theta = 22.5^\circ$ cone caps, and the sections of the missing ‘equatorial’ band (white) surrounding them. $C_A$ equals the sum of the areas highlighted red and blue divided by the area of the red region.

For the PHE simulated workplace field environment, for which most of the dose directionality is anticipated to originate just from horizontal exposures, the additional field mapping may be achieved by the inclusion of two cones with their axes vertical (Figure 1.16, left). The fluence tallied in the upwards orientated cone may then be convolved with the SS-ISO dose conversion coefficients to provide the total component of effective dose from ‘above’, whilst the fluence tallied in the downwards orientated cone may be convolved with the SI-ISO dose conversion coefficients to provide the total component of effective dose from ‘below’. For the SCK-CEN field, which is more anisotropic than the PHE field, additional cones need to be defined in directions other than vertical and horizontal planes. But apart from this added complexity, the overall procedure and areal correction method (see below) at SCK-CEN follow the same general logic to field mapping as at PHE.

Mathematically, the set of cones defined at each location provides a set of caps on the unit sphere about that point. However it is obvious that these caps will not tessellate, which implies that even if they were all tangential, they would not cover all of the solid angle about the sphere’s centre. As a result, a correction is required to account for those directions for which fluence components are not included. This is essentially achieved by weighting each cone’s contribution by the area of the adjacent region that it is not covering. To illustrate the general method, consider a scenario in which 8 horizontal cones of opening half-angle $\theta = 22.5^\circ$ are defined, the caps of which are all tangential to the caps of 2 vertical cones of opening half-angle $(90-\theta)^\circ$, as shown in Figure 1.16 (right). Assume also that the ‘equatorial’ band around the horizontal cones is divided equally into 8 identical longitudinal sections. Then, the area of the region adjacent to each of the horizontal caps that it is not covering (Figure 1.16, right), i.e. the ‘missing’ components of the solid angle that are not being tallied by the cones in the Monte Carlo model, can be shown to equal $[4\cos\theta + \sin\theta - 4] \pi/2$, and the correction factor, $C_A$, for the effective dose calculations is:

$$C_A = \sin\theta / [4-4\cos\theta]$$  \hspace{1cm} (1)
Thus, multiplying the result from each of the horizontal cones by $C_A$ provides the final estimate of the fluence in those directions. From Equation 1 for a half-angle of $\theta=22.5^\circ$, a correction factor of $C_A = 1.257 \times$ is found to be appropriate. By applying this to the fluence results the entire $4\pi$ solid angle becomes accounted for at each location.

When only 8 horizontal and 2 vertical cones are required, such as is the case for the PHE field, the dose mapping on the grid can be achieved through the use of five input files (= 4 sets of opposite pairs of horizontal cones + 1 opposite pair of vertical cones). When the results from these calculations are variously combined, it provides effective dose rate data for individuals orientated in eight different directions at each position on the grid. Four of these input file geometries are shown in Figure 1.18 for the PHE workplace field, with the cone structure also illustrated; the absent fifth input file relates to the vertical cones, which would protrude in and out of the page at each grid location. The PHE facility is symmetric about the central axis, so only the lower half of the room has been mapped; the green blocks indicate the water moderator, with the $^{241}$Am-Be source just to their left.

II.2.2 Use of radiation monitors for normalization

MCNP provides its results relative to ‘per-source-particle’: normalization to the source activity (or other appropriate parameter, e.g. fluence) is therefore necessary to obtain absolute dose rates. In environments where the rates might be changing, such as transient geographies (e.g. storage facilities) or situations where neutron fluence rates can fluctuate (e.g. accelerator facilities), it would be necessary to vary the normalization in real-time in order to derive the synchronous dose rate map.

For globally changing fields, i.e. those in which the relative dose rate at adjacent locations on the grid is fixed but the absolute magnitude at each of these can vary according to a single time-dependent scaling factor, the recommendation is to make use of an installed ambient dose equivalent monitor in the room. The response of this monitor relative to the dose rates at each location of the grid can be determined by Monte Carlo modelling, and normalized in the same way upon implementation of the PODIUM system. Any increase or decrease in the reading by this monitor from its baseline value thus provides a scaling factor that can be applied uniformly to all the other dose rates on the map. Of course, alarming capabilities could also be incorporated into this approach.

For locally changing fields, i.e. those in which the relative dose rate at adjacent locations on the grid varies in a time-dependent way, several installed ambient dose equivalent monitors would be required in the room. Use of these to provide time-dependent scaling factors would proceed similarly to the method for globally changing fields, but with different correction factors being applied on a local basis. Of course, the number of such monitors required, their locations, and which locations on the grid each would relate to, would all depend on the gradients within the room that the dose rates are expected to change with.
V. Conclusions of Task 1.2
As regards interventional radiology workplaces the required information and the foreseen data sources have been identified. In particular, for the calculations the most reliable way to gather the required information is the RDSR report. This information is of interest for the two dosimetric approaches considered in the project. The PODIUM application up-loads the information from the RDSR and transforms it to be used as input for the dose calculation. A sensitivity analysis on the impact of different parameters on the operator dose has been carried out to optimize the size of the radiation field lookup table.

For neutrons, the real-time Monte Carlo method is not feasible due to the time constrains being unrealistic for such computationally intensive simulations, as well as problems with the calculation method itself. Therefore, a lookup method is used where the workplace simulations must be performed before the application of the proposed real-time dosimetry system. The workplace characterization will result in lookup tables defined on grids with locational- and directional- (the facing direction of the individual) dependent effective dose conversion coefficients. This system will depend on a monitor to scale the lookup value with the instrument’s reading. The lookup table is highly dependent on the workplace and the neutron sources, but can be calculated in advance using the Monte Carlo method without the time constrains of a real-time system. For these calculations to be performed detailed knowledge of the sources and workplace environment are needed.

VI. References of WP1


WP2: Dose simulations using computational phantoms and Monte Carlo methods

Task 2.1: Development of phantoms that can be used in the Monte Carlo calculations

Computational phantoms and their role in PODIUM

The objective of the first task of PODIUM WP2 was to provide a set of computational phantoms to be used for calculating occupational doses with Monte Carlo (MC) simulations. In consideration of the requirements of WP2 and of the other Work Packages, we decided to deliver four phantoms. These phantoms were selected to represent a heterogeneous cohort of workers with different sex, statures and postures. These were: the Realistic Anthropomorphic Flexible (RAF) phantom [1] in two postures – a standing posture with arms stretched away from the body and leaning forward with hands above the patient’s body – and two female voxel phantoms (one slim, one big) from the HMGU voxel phantom family [2].

I.1 B-Rep phantoms: Realistic Anthropomorphic Flexible phantom and Interactive Posture Program

The Realistic Anthropomorphic Flexible phantom [1] belongs to the B-Rep generation of computational phantoms. The RAF phantom represents an average Caucasian adult male, so its anthropomorphic measurements (176 cm, 76 kg) are close to those of the ICRP reference adult male. Differently from the ICRP reference voxel phantom, however, the RAF phantom is made of polygonal mesh (PM) surfaces, a type of B-Rep. The PM representation is, by far, the most widespread computer graphic modelling technique. For this reason, modern computer hardware was evolved and optimized to work with PM. GPUs can process billions of polygons per second, making it possible to apply complex mathematical operations to deform the mesh surfaces in real-time.

For making use of RAF phantom in PODIUM applications, we developed a software, named Interactive Posture Program (IPP), which allows making use of the RAF phantom through a simple interactive user interface, illustrated in figure 2.1a. With IPP, the posture of the RAF phantom is controlled by nine selectable objects, called end-effectors. Five end-effector are used to define the point that needs to be reached by each limb (hands, feet and head of the phantom). Additionally, four end-effectors can be turned on to adjust finely the orientation of elbows and knees. Thanks to IPP, the RAF phantom could easily be shared among PODIUM partners, who were then able to create versions of phantoms mimicking realistically the workers posture. For assessing correctly doses to medical staff in Interventional Radiology, protective garments were included in our simulations. For this reason, in IPP the RAF phantom can also be equipped with an apron, a thyroid collar and a cap (all 0.5 mm thick). The garments are activated through a toggle in the IPP interface (figure 2.1b).
Figure 2.1: a) graphical interface of the Interactive Posture Program (IPP) for controlling the posture of the RAF phantom, and b) RAF phantom equipped with protective garments.

Furthermore, a special processing within IPP was developed that converts the RAF phantom either to mesh files compatible with Geant4 or to a voxel phantom, compatible with most MC transport codes (MCNP, EGS, Penelope, Geant4).

I.2 Voxel phantoms

The following voxel phantoms from the HMGU phantom family [2] were used for the PODIUM project: Irene and Donna. Irene is a slim person (51 kg, 163 cm), and Helga is large (79 kg, 176 cm). Furthermore, RCP-AF and RCP-AM, the ICRP/ICRU reference adult computational phantoms, are also used [3].

For the simulations in the interventional radiology workplaces, the phantoms Donna and Irene have been equipped with protective garment (apron and collar). This garment is represented by one voxel layer of protective material surrounding the phantom outline (see Fig. 2.2). The material and density of this voxel layer had to be assigned in the MC simulations such that the voxel dimension properly reflects the material and thickness of the protective garment. For Donna and Irene, whose voxel in-plane resolution is 1.875 mm, a “modified” lead density of 3.0267 g cm$^{-3}$ was used to simulate 0.5 m of lead (compared to the physical lead density of 11.35 g cm$^{-3}$). For the purpose of distinction from the original phantoms, the phantoms with protective garment were renamed to “Donna2018” and “Irene2018”.

Figure 2.2: Transversal slice of Donna2018 at height of the breast with added voxel layer representing a protective apron.
The voxel phantoms Irene2018 and Donna2018 with protective garment have been stored on the restricted area of the PODIUM website. They can be made available to the scientific community upon request.

Task 2.2: Establishment of a pre-calculated database of fluence to dose conversion coefficients for photons and neutrons for different phantom positions, postures, and statures and for different irradiation geometries and energies

Fluence to dose conversion coefficients and their role in PODIUM
The objective of Task 2.2 is to provide a library of pre-calculated conversion coefficients as a first approach of the fast online dosimetry application for workers in the realistic workplaces of WP4 (interventional radiology) and WP5 (neutron fields). Especially for neutron dosimetry, it was to be expected that fast (i.e., real-time) Monte Carlo radiation transport would not be feasible within the duration of the PODIUM project. For photons, the database of pre-calculated fluence to dose conversion coefficients can back up the fast Monte Carlo calculations of Task 2.3.
This database covers different relevant phantom statures and positions in the field as well as photons and neutrons of different energies and in different irradiation geometries. The numerical data of the conversion coefficients have been uploaded to the STORE database and can be found at DOI:10.20348/STOREDB/1156.

II.1 Fluence to dose conversion coefficients for photons
The photon conversion coefficients were aimed at serving the needs of the workplaces considered in the frame of the PODIUM project, i.e., interventional radiology. Hence, phantoms with protective lead garment were used for the simulations, and radiation incidence was limited to (a) the upper part of the body and (b) anterior and anteriorly oblique directions of photon incidence. To account for the inhomogeneous radiation incidence on the body, the body was sub-divided into six smaller sections (called “panels”) for which separate conversion coefficients were calculated. There were three panels in height (called “Top”, “Mid”, and “Bottom”), on both sides (left and right). On each of these panels, incidence of parallel mono-energetic photon beams under various angles was considered. Angles in horizontal directions ranged from 60° left-anteriorly oblique (“LAO60”) to 60° right-anteriorly oblique (“RAO60”), in steps of 15°. Anterior radiation incidence is corresponding to 0°. The angles in vertical directions ranged from 30° upward (“Up30”) to 30° downward (“Do30”), also in steps of 15°, where horizontal incidence is corresponding to 90°. All combinations of horizontally and vertically oblique angles were considered. An illustration of the terminology used for the panels and the incidence angles is shown in Figure 2.3. The photon energies were ranging from 10 keV to 120 keV in steps of 10 keV.
For all six panels, all nine horizontally varying incidence angles were considered, i.e., LAO60, LAO45, LAO30, LAO15, AP, RAO15, RAO30, RAO45, and RAO60. Relevance of the vertically varying incidence angles depended on the location of the panel in height: for the Top panels, only upwards oriented angles were considered; for the Mid panels, upwards and horizontal angles were considered, and downward angles were considered only for the Bottom panels.

Conversion coefficients were calculated for two voxel phantoms representing a large (“Donna2018”, 176 cm, 79 kg) and a slim female (“Irene 2018”, 163 cm, 51 kg), as well as a reference-sized male mesh phantom “RAF”. For the RAF phantom, two different postures were considered – (a) an upright posture with arms away from the body and (b) leaning forward with the hands above the patient body. Figure 2.4 shows the voxelized versions of the RAF phantom in the two postures.

Examples of fluence to effective dose conversion coefficients for selected panels, incidence angles and photon energies are shown in Figures 2.5-2.7.
Figure 2.5: Effective dose per fluence conversion coefficients for photons of energy 120 keV for the Bottom left (BL) and Bottom right (BR) panels of the RAF phantom. The x-axis is representing different horizontal angles, and each vertical angle is represented by a different curve.
Figure 2.6: Effective dose per fluence conversion coefficients for the most common AP horizontal radiation incidence of the RAF phantom. The x-axis is representing photon energy, and each panel is represented by a different curve.

Figure 2.7: Effective dose per fluence conversion coefficients for the most common AP horizontal radiation incidence of the standing and leaning postures of the RAF phantom. The x-axis is representing photon energy, and each panel is represented by a different curve.

It can be seen that generally the conversion coefficients for Irene2018 are higher than those for Donna2018 and RAF phantom, due to her smaller body resulting in reduced self-shielding. The lead apron has relatively less attenuating effect below its 88 keV K-edge, which accounts for the fall in the effective dose contributions behind the lead apron, which give minima at 100 keV.

In Figure 2.6, the effective dose contribution from the most common field panel AP directions is shown for the RAF phantom. As expected, the major contribution to the effective doses is due to the middle field panels (MR and ML), as they cover the largest section of the RAF phantom, i.e. the upper torso, which also includes some of the most radiosensitive organs. On top of this, for the most common rotation angles of the C-Arm and positions of the doctor, the highest fluence is often impinging on the middle panels.

A few examples of fluence to effective dose conversion coefficients for both postures and for selected panels, incidence angles and photon energies are shown in Figure 2.7. Similar to these graphs, also the other tables of the RAF phantom show that the forward leaning posture has a relevant impact on all Field Panels. In the
great majority of the cases, effective doses for Bottom panels decreases with the leaning posture, while the effective doses for Mid and Top panels increases.

II.2 Fluence to dose conversion coefficients for neutrons
For neutron workplaces, the fields are much more homogeneous than the photon fields in interventional radiology. Hence, only broad parallel beams incident on the whole body had to be considered. The conversion coefficients that are required are largely available in ICRP Publication 116 [4], but additional angles were required for the workplace calculation because it was considered that the published data were too coarse in direction resolution for the purpose of online dosimetry.

The additional angles of incidence are horizontal and 45° upwards: along the vertical axis and along the horizontal axis, it is from 0° to 315°, in steps of 45° with the 0° being from the right side of the phantom to the left side of the phantom. To derive effective dose coefficients, two phantoms calculations needed to be done: the Adult Female and Adult Male phantom. The Adult Female is the slimmer phantom compared to the Adult Male, with less mass and height. The (pseudo) effective dose per neutron fluence conversion coefficients are calculated for the Adult Female and Adult Male phantom and the ratio is derived: $E_{\text{pseudo,AF}} / E_{\text{pseudo,AM}}$, for the various 45° upward beams: this is shown in Figure 2.8. The ratio of (pseudo) effective dose ratio between Adult Female and Adult Male is always between 1.00 ± 0.20 and this is well within the uncertainty required for personal dosimetry. Where the ratio is above 1.0 the neutron effective dose conversion coefficients are higher for the smaller body, as is the case with the photons. This is especially the case for the PA direction of the 45° upwards beam. As most sensitive organs are more oriented towards the front side of the phantoms, and the neutron beam is entering from the backside of the phantom, there will be more tissue attenuating the neutron beam for the bigger phantom resulting in a lower neutron energy and therefore a smaller dose.

For the AP direction, the 45° upwards beam the ratio above and below 1.0 occurs, depending on the neutron energy. However, where the effective dose conversion coefficient ratio is below 1.0, the opposite is true, and the smaller body supplies the lower effective dose conversion coefficients. This is especially true for both lateral 45° upwards beam directions. Looking at more detail to the difference of the phantoms shows that the difference in the lateral dimension is only 2%, whereas the difference in the front back dimension is 12% and in the height 5%. This makes that for the lateral dimensions the Adult Male intersects with more neutrons than the Adult Female and the attenuation properties are not that dissimilar compared to the lateral dimensions and therefore the Adult Male phantom absorbed more energy than the Adult Female and dividing by the phantoms mass results apparently in the higher neutron effective dose per fluence conversion coefficient for the Adult Male phantom.
Figure 2.8: Ratio of the pseudo effective dose per fluence conversion coefficient for the Adult Female / Adult Male phantom for various neutron energies, and various horizontal angles (first in legend) and the vertical 45° upwards (second in legend) direction.

For the neutrons and the broad parallel beams, the position of the legs and arms is far less important than for instance for photons beams in the interventional radiology / cardiology case. The approximation of using the various angles, especially the 45° upward direction, as being equivalent to a person bending 45° forward with a horizontal beam, and therefore the standing 45° upward beam direction can be used, to approximate this posture with the neutron dose conversion coefficients.

Task 2.3: Feasibility study towards application and improvement of fast MC codes for online dosimetry in interventional radiology

It was foreseen to provide fast dose calculations by using two approaches. The first approach would use a library of pre-calculated conversion coefficients, while the second one would be based on the use of fast Monte Carlo (MC) simulations with the MC-GPU code and other accelerated calculations with standard codes such as PENELOPE. The main aim of task 2.3 was to test the speed and resulting accuracy of the latter approach, based on MC codes. Two fast MC codes were developed for interventional radiology:
- MCGPU-IR.
- PENELOPE/penEasyIR.

The following sections describe the methodology applied in both systems. The MC results are compared with the measurements and, finally, an analysis of calculation speed is presented.
Methodology

The two fast Monte Carlo approaches used for the dose calculations read input files adapted by the PODIUM application. The DCA organizes them as it is required by each Monte Carlo code. In interventional radiology workplaces the scattered radiation field that reaches the medical staff should be calculated with clinic and patient specific data, but for both MC codes the same basic information is needed. The most important data is detailed in the following section.

I. Radiation field required information

Some of the needed data correspond to the physical configuration of the X-ray tube, this could be considered as fixed values for a specific room and gathered during the setting-up of the dosimetry application in the facility. However, there are patient specific data that have to be retrieved in real-time or at least be available at the end of a procedure:
- Sex, height and weight of the patient.
- Anatomical region examined-procedure type. If the position of the C-arm and/or the origin of table movements are not well known, this information could be alternatively used.
- For each projection/irradiation event:
  o Date/time it started, duration.
  o Focal spot position.
  o Shape and size of the radiation field.
  o Source to image intensifier distance.
  o Source rotation angles.
  o kVp (kV).
  o Added filtration.
  o Dose at the reference point, for normalization purposes, or the dose area product (DAP).
  o Position of the reference point.
  o Position of movable protective elements (table shields, ceiling-mounted or wall-mounted shields...).
  o Patient’s table position (x,y,z) in (cm).

For the PODIUM project the preferred source to retrieve this data will be the Radiation Dose Structured Report (RDSR), which is generated at the end of the medical procedure.

I.1 Radiation source description

For both MC codes the X-ray beam is computationally collimated to produce a rectangular field on the image intensifier plane according to the field size and shape indicated in the RDSR. The image intensifier is automatically located at the specified distance right in front of the source focal spot, with the collimated beam pointing towards the geometric centre of the detector. The energy distribution of the X-ray beam is generated according to the X-ray systems characteristics and procedure specific data (anode material and anode angle; inherent and added filtration, kVp). Differences between the doses calculated by the PODIUM system (based on SPEKTR [5]) and XCOMPSR [6], which is a well-known code, are lower than 2 %.
I.2 Normalization to absolute values

All Monte Carlo codes need a normalization factor \( N \) to refer the simulated absorbed dose per history to the real number of emitted photons.

\[
N = \frac{\text{entrance air kerma}}{K_a} \quad (2.1)
\]

For each irradiation event (fixed kV, filtration, angulation and field size values), \( N \) is calculated from the ratio between experimental entrance air kerma and simulated air kerma \( (K_a) \) or energy deposited at a point of interest. \( K_a \) must be calculated in a point where there is no influence of backscatter in order to simulate same conditions as experimental entrance air kerma value.

In general, the experimental entrance air kerma at the point of interest will be calculated following the inverse square law from the dose area product (DAP) value divided by the radiation field-size, both values supplied in the RDSR (see equation 2.2). As an alternative, the dose at the reference point reported in the RDSR can also be used. It is worth mentioning that in the energy range of interventional radiology kerma and absorbed dose are assumed to be equal.

\[
\text{entrance air kerma} = \frac{\text{DAP}}{\text{field size}} \cdot \frac{(\text{distance source} - \text{detector})^2}{(\text{distance source} - \text{point of interest})^2} \quad (2)
\]

II. PENEOLOPE/penEasyIR

PENEOLOPE/penEasyIR is based on PENEOLOPE v2014 [7], a standard general-purpose MC code. The code performs Monte Carlo simulation of coupled electron-photon transport in arbitrary materials for a wide energy range, from a few hundred eV to about 1 GeV. Photon transport is simulated by means of the standard, detailed simulation scheme. The code is freely distributed by the OECD Nuclear Energy Agency Data Bank (https://www.oecdnea.org/databank) and, in North America, by the Radiation Safety Information Computational Centre of the Oak Ridge National Laboratory (https://rsicc.ornl.gov). The core of the system is a set of Fortran subroutines that run in central processing units (CPU). Besides, penEasy [8] is a general-purpose main program for PENEOLOPE that includes a set of source models, tallies and variance-reduction techniques that are invoked from a structured code. The program has been modified for the specific purposes of PODIUM project in the interventional radiology field, and the new program has been named penEasyIR. As a whole, the system will be called from now on PENEOLOPE/penEasyIR.

To speed-up the simulation process by using a general-purpose MC code such as PENEOLOPE, two main approaches have been used:
- Use of a variance reduction technique to calculate operator doses. In particular the Detection forcing technique implemented in PENEOLOPE/penEasyIR as tally ‘Photon Fluence Point’ (now publicly available in penEasy v20190921 (https://inte.upc.edu/en/downloads).
- Simplification of the geometry of the problem.

II.1 Detection forcing technique

The PENEOLOPE/penEasyIR tally Photon Fluence Point virtually computes the photon fluence spectrum at a detection point specified by its position coordinates. The fluence can be defined as the number of photons per unit area reaching a small test sphere centred at the point of interest. A direct application of this definition to calculate the scattered field that reaches the medical staff in interventional radiology is impractical. A more effective approach is to use a detection forcing technique. The idea underlying the method is that, instead of counting photons that actually reach the test sphere, the probability per unit cross
sectional area of reaching the sphere is tallied. Afterwards the linear attenuation coefficient (i.e., inverse mean free path) of the m-th material encountered by the virtual photon along its straight line path towards the point of interest and the distance travelled in that material is taken into account to compute the probability to reach the test sphere.

The fluence produced by the present tally is not equivalent to the one produced with the tally Fluence Track Length, which is fully consistent with PENELOPE's physics. To prevent some statistical fluctuations and non-convergence of the results, an exclusion sphere (1 cm radius) surrounding the detection point has been included.

By using this technique the simulation times are drastically reduced. In a typical interventional radiology procedure where only scattered radiation reaches the medical staff, up to several days would be needed to calculate the absorbed doses at the point of interest with PENELOPE/penEasy without any variance reduction technique applied (statistical uncertainties lower than 1%, k=1). On the contrary, with PENELOPE/penEasyIR the simulation times are reduced to tens of seconds, with similar statistical uncertainties.

II.2 Simulation process
PENELOPE/PenEasyIR provides the photon energy fluence distribution at a given position and subsequently fluence to dose conversion coefficients are automatically applied to obtain the operational quantities: $H_p(10)$, $H_p(3)$, $H_p(0.07)$.

II.3 Patient anatomical description
The simulation speed highly depends on the complexity of the geometrical description of the problem. The simulation of a complex patient description needs calculations six times longer than a simplified phantom to obtain results with a comparable uncertainty. Therefore, to speed-up the simulation process, a simplified humanoid phantom has been selected for the patient anatomical description made of one single material (ICRU tissue) which also provided accurate results, within accepted uncertainties. PENELOPE/PenEasyIR describes the patient by means of quadric surfaces (spheres, cylinders...). In general the selected geometry is a BOMAB-like phantom, but other geometries can be easily used. The BOttle Mannequin ABsorber (BOMAB) phantom provides a functional simulation for the scattering of radiation in an adult human figure 170 cm tall and is immersed in air.

II.4 Phantom scaling
In order to adapt the phantom's dimension to the patient characteristics, the body mass index (BMI) is applied by defining a linear correlation between BMI and waist perimeter for both men and women (data obtained from [9]). First, the height of the phantom is scaled to adjust exactly to the height of the patient. The two other dimensions (width and depth) are obtained comparing the BMI values with the waist perimeter. Note that we are assuming the phantom waist as a perfect ellipse. Depending on the irradiated part of the body, another organ could be considered for normalization.

Figure 2.9: PENELOPE/penEasyIR patient description.
II.5 Operator positioning and normalization to absolute values
Photon energy fluence is simulated at up to 4 (in a single run) points in air, matching operator Kinect joints (Points B in Figure 2.10). The normalization is calculated at the same time than the operator doses. To do so, the geometry already contains an air box where the air kerma is calculated by using the ‘Track fluence length’ tally.

$H_p(10)$ received by the operator is calculated applying Equation 6 [10]. Similarly $H_p(0.07)$ and $H_p(3)$ can be calculated with the same equation but using, respectively, $(H_p(0.07,0º)/K_a)$ and $(H_p(3,0º)/K_a)$ from [11] instead of $(H_p(10,0º)/K_a)$.

$$H_p(10) [\mu Sv] = N \cdot F \cdot \sum_{i=1}^{n} \phi_i^{sim} \cdot \left(\frac{\mu_{tr}}{\rho}\right)_i \cdot E_i \cdot \left(\frac{H_p(10,0º)}{K_a}\right)_i$$  \hspace{1cm} (6)

Where
- $N$ is the normalization factor.
- $F$ is a unit normalization factor $1.602 \cdot 10^{-13} [J \text{ g} \text{ kg}^{-1}]$
- $\phi_i^{sim}$ is the simulated energy fluence, from Tally Photon Fluence Point, for energy region $i$ at point B $[\text{cm}^2 \text{ eV}^{-1} \text{ per history}]$.
- $\left(\frac{\mu_{tr}}{\rho}\right)_i$ is mass energy-transfer coefficient for energy region $i$ $[\text{cm}^2 \text{ g}^{-1}]$ which at those energies is comparable to $\left(\frac{\mu_{en}}{\rho}\right)$ and can be interpolated from NIST [12].
- $E_i$ is the middle energy for energy region $i$ [eV].
- $\left(\frac{H_p(10,0º)}{K_a}\right)_i$ is the conversion coefficient from air kerma free-in-air to $H_p(10,0º)$ in an ICRU slab for energy region $i$, interpolated from ICRP 74 [10].

II.6 Simulation of ceiling-mounted shields
PENELOPE/penEasyIR allows the user to define a shield interposed between the main operator and the radiation source by indicating the material composition and dimensions, however to do it automatically the camera system should provide the position and orientation of the shield. At present, when shields are used, the geometry files have to be prepared manually.

![Image](image.png)

**Figure 2.10:** Scheme of geometry used in PENELOPE/penEasyIR simulation.
III MCGPU-IR

MCGPU-IR is based on MC-GPU [13], being the latest version of this software the one released in 2012. MC-GPU is a Monte Carlo simulation code that generates synthetic radiographic images and computed tomography (CT) scans of realistic models of the human anatomy using the computational power of commodity Graphics Processing Unit (GPU) cards. The code implements a massively multi-threaded Monte Carlo simulation algorithm for the transport of X-rays in voxelized geometries. The X-ray interaction models and material properties were adapted from PENELope v2006. The interaction sampling and geometry ray-tracing algorithms were designed to provide an optimum performance in GPUs, minimizing the accesses to the slow video memory while maximizing the parts of the code that can be executed in parallel in thousands of concurrent GPU threads.

MC-GPU was developed using the CUDA programming model from NVIDIA to achieve maximum performance on NVIDIA GPUs. The code can also be compiled with a standard C compiler to be executed in a regular CPU; however it has been tested only in the Linux operating system. In a typical medical imaging simulation, the use of GPU computing with MC-GPU has been shown to provide a speed up of between 20 and 40 times, compared to the execution on a single CPU core.

The source code of MC-GPU is free and open software in the public domain, and is distributed from the website: https://code.google.com/archive/p/mcgpu/.

In 2013, A. Badal et al. developed MC-GPU beta [14], an extension of the original MC-GPU which added some new features, being the most important one the possibility to simulate staff doses (single operator); and afterwards the possibility of simulating shields interposed between the source and the operator. MC-GPU beta is not yet publicly available. MC-GPU beta has been modified during PODIUM project to speed-up the simulations. The new version allows an automatic simulation of the source parameters, updates physical models, and finally corrects some programming bugs. It is specifically designed for interventional radiology and will be called from now on MCGPU-IR.

To speed-up the simulation process two main approaches have been used:
- Parallelization among several GPU cards by the implementation of MPI libraries.
- A set of functions have been developed to automatically set the optimal values for:
  - Number of blocks per kernel.
  - Number of threads per block.
  - Number of histories per thread to be simulated in the GPU.

The non-optimized code running in one single (GPU) needed longer simulation times (up to a factor of 4) than the optimized code running with two GPU cards.

III.1 Simulation process

In MCGPU-IR two simulations are successively launched: a simulation with the patient anatomy to compute the patient average and peak organ doses and 3D dose map, and a separate simulation with the operator anatomy to estimate the operator doses. During the simulation with the patient anatomy all the particles escaping the simulation universe are tested for intersection with the operator bounding box. Those X-rays scattered in the direction of the operator are stored in a phase space file (PSF) in GPU memory. When the simulation with the patient finishes, a new simulation with the operator anatomy is started using the PSF as the X-ray source. Since only a small fraction of the initial X-rays are expected to be scattered towards the
operator, each X-ray in the PSF is recycled many times to maximize the information obtained from each particle as an intrinsic variance reduction technique. At the end MCGPU-IR provides absorbed dose at a voxel level, the absorbed dose in the different specified organs in the phantom file (if the voxelized phantom is segmented), and finally the effective dose is computed (ICRP, 2007).

### III.2 Patient/operator anatomical description

During PODIUM, MCGPU-IR used the voxelized Rex or Regina phantoms developed by Helmholtz Zentrum München - HMGU (Figure 2.11).

![Figure 2.11: REX and REGINA voxelized phantoms.](image)

For PODIUM, the 143 tissues from the original phantoms were reduced to 26: air surrounding; cortical bone; spongy bone; heart; remaining tissues (soft tissue); front skin trunk; back skin trunk; other skin (extremities); blood; muscle; cartilage; lung; oesophagus; thyroid; bladder; liver; bone marrow; breast adipose; breast glandular; colon; stomach; gonads (ovaries & testes); salivary glands; brain; eye lens left; eye lens right. This organs segmentation allows calculating the effective dose and the dose equivalent of extremities and of the lens of the eye.

\[ H_p(10) \] is calculated as the mean absorbed dose at eight voxels made of ICRU tissue at a depth of approximately 1 cm, at the position of interest.

### III.3 Phantom scaling

The phantom scaling methodology is the same than for PENELlope/penEasy, but the waist perimeter for Rex and for Regina is calculated measuring the two perpendicular dimensions of their waist and assuming it forms a perfect ellipse.

### III.4 Operator positioning

For each irradiation the operator is located in the position obtained from the camera tracking. The location of the main operator is determined at the beginning of each irradiation event and it is kept constant all along the event. A more complex simulation scheme with multiple time steps could be implemented if sufficient computational resources were available.
MCGPU-IR needs 4 points to locate the operator: Head; Left Shoulder; Right Shoulder and Hip (labelled as Spine Base in tracking, see Figure 2.12.

**Figure 2.12:** Data for operator positioning (left), patient/operator coordinate systems (right).

![Diagram of human body with markers indicating head, shoulders, and hip](image)

The position is calculated from the Hip location as shown in Figure 2.13. The hip position \((x, y, z)\) determines the distance from the origin of coordinates in MCGPU-IR (left foot of the patient) to the middle point in width and height of the operator. The other three points needed (shoulders and head) are used for the rotations of the operator phantom, bending over the table and not perpendicular to the table.

**Figure 2.13:** Criteria for positioning the operator using Kinect hip joint location.
III.5 Normalization to absolute values
For each irradiation event (fixed kV, filtration, angulation and field size values), the air kerma at the reference point (which position is indicated in the RDSR) is calculated by simulating the irradiation of a small box of air centred at the corresponding distance.

III.6 Simulation of ceiling-mounted shields
MCGPU-IR allows the user to define a shield interposed between the main operator and the radiation source, however to do it automatically the camera system should provide the position and orientation of the shield. At the present stage of PODIUM project, when shields are present, the geometry files have to be prepared manually.

IV. Computational resources
PENELOPE/penEasyIR and MCGPU-IR run in the Argos Cluster from INTE-UPC compounded by the several machines. PENELOPE/penEasyIR uses CPU and it runs in any available node in the cluster. MCGPU-IR instead, uses GPU and it runs only in one node (called c15) with compatible NVIDIA graphic cards.

Speed and accuracy tests
IV.1 Accuracy tests
The accuracy of MC systems has been analysed in a controlled experimental set-up at Malmö Hospital (Sweden). Measurements were performed on a static phantom. 2 TLD detectors type TLD 2000C (DC) and 2 Thermo Electron Corp type EPD MK (EMD) for $H_p(10)$ were used for each measurement. The main operator was represented by a CT Torso phantom CTU-41 (Kyoto Kagaku) and the patient phantom was a CIRS Phantom (Adult Male Phantom Model NO. 701). The R100 dose probe (RTI) was used for the measurements in the radiation field.

Figure 2.14: CIRS Rando phantom (left), experimental set-up (center), CT Torso phantom (right).

Two different measurements with the C-arm irradiating the patient on the chest were performed. The first measurements were from 0-degree straight below the phantom and the second measurement was with a 15-degree angle. All machine parameters were taken from the DICOM Radiation Dose Structured Report (RDSR) generated during the exposures. The ceiling mounted lead protection was not used during this case. The position of the dosemeters for each measurement are given below in Figure 2.15.
Figure 2.15: Shows the position of the TLDs and EPDs from each separate measurement.

With PENELOPE/penEasyIR, patient geometry has been simulated by using different geometries to study the influence of the patient’s adapted geometry on the accuracy of the simulated results:
- As a prism (slab) made of soft tissue (ICRU four-component).
- As a BOMAB like phantom, adapted to the real case: chest adapted and without arms and legs, made of soft tissue.
- As a non-scaled stylized phantom without arms/legs. 4-materials are considered: bone compact (ICRU), soft tissue (ICRU), skin (ICRP), lung (ICRP). In Figure 2.16, to show the defined internal organs, soft tissue and skin has been removed for visualization purposes.

Figure 2.16: Geometry of prism phantom (left), adapted BOMAB phantom (centre), stylized phantom (right).

With MCGPU-IR, patient geometry has been simulated by using different geometries to study the influence of the patient’s adapted geometry on the accuracy of the simulated results:
- As a prism (slab) made of soft tissue (ICRU four-component) with the dimensions indicated in Figure 17.
- CT scan of the CIRS Rando phantom, dimensions indicated in Table 6.
- REX scaled phantom (arms and legs included).
- REGINA scaled phantom (arms and legs included).
As mentioned before patient and operator share the same geometry, therefore it means that when, for instance, a CIRS Rando phantom is used to describe the patient, the operator is described by using the same geometry, a CIRS Rando phantom, although the dimensions of the operator and the patient could be scaled separately.

**IV.2 Analysis of results**

Tables X and X show the simulated \( H_p(10) \) compared with the experimental measurements for each detector and each experiment, including the associated uncertainty (\( k=1 \)). In the case of Monte Carlo data the uncertainty takes into account the statistical uncertainty and an uncertainty of 10% (\( k=1 \)) associated to the air kerma value used in the normalization. Simulation times were around 120 s.

**Table 2.1: Experiment 1**

<table>
<thead>
<tr>
<th>Experimental ( H_p(10)/\mu Sv )</th>
<th>PENEOLOPE/penEasyIR ( H_p(10)/\mu Sv )</th>
<th>MCGPU-IR ( H_p(10)/\mu Sv )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prism</td>
<td>BOMAB</td>
</tr>
<tr>
<td>EPD1 73 ± 8</td>
<td>66 ± 7</td>
<td>84 ± 9</td>
</tr>
<tr>
<td>EPD2 72 ± 8</td>
<td>56 ± 6</td>
<td>80 ± 8</td>
</tr>
<tr>
<td>DC52 134 ± 13</td>
<td>84 ± 8</td>
<td>94 ± 9</td>
</tr>
<tr>
<td>DC48 85 ± 8</td>
<td>63 ± 6</td>
<td>72 ± 7</td>
</tr>
</tbody>
</table>

As can be observed, for PENEOLOPE/penEasyIR the geometry description can influence the final result, up to a 30% (experiment 1, EPD2 position) when a prism or the BOMAB phantoms are compared. The use of a stylized phantom can influence the result up to a 40% (experiment 2, DC36 position) when a BOMAB or the stylized phantoms are compared.

As regards MCGPU-IR the geometry description can influence the final result, up to a 35% (experiment 1, EPD1 position) when a prism or the Rando phantom are compared. In addition, when using the REX or REGINA phantoms, the phantom scaling can influence up to a factor of 1.7 (experiment 2).

Taking BOMAB and Rando phantoms data as the best estimates for PENEOLOPE/penEasyIR and MCGPU-IR respectively, the results are considered satisfactory. The ratio obtained varied between 0.77 and 1.15 for the 4 EPDs measurements for PENEOLOPE/penEasyIR, 0.63 and 1.10 for MCGPU-IR. As regards the comparison with the 3 TLDs, the ratios are of the same magnitude.

Finally, to highlight the influence on effective doses of the selection of the voxelized phantom, the effective doses for the scaled REX phantom and the scaled REGINA phantom were computed. Table 2.3 shows that a difference up to a 30% would be expected by using one or the other.
Table 2.3: Calculated effective dose for different patient/operator voxel phantoms.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$E/\mu\text{Sv}$ (Scaled REX)</th>
<th>$E/\mu\text{Sv}$ (Scaled REGINA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$28 \pm 3$</td>
<td>$35 \pm 3$</td>
</tr>
<tr>
<td>2</td>
<td>$21 \pm 2$</td>
<td>$27 \pm 3$</td>
</tr>
</tbody>
</table>

IV.3 Simulation speed tests

Several speed tests have been carried out to estimate the shortest simulation time that can produce results with a comparable accuracy and acceptable uncertainties. The simulated problem corresponded to the one described in the previous section to assess the accuracy of the codes.

For PENELLOPE/penEasyIR, simulation times (use of CPU time) between 2 to 120 seconds have been tested. The absolute values obtained for a simulation time of 2 s agreed with those obtained for 120 s within statistical uncertainties (4%, $k=2$). Therefore it can be concluded that the simulation time can be drastically reduced, however, the global simulation time is also dependent on the time devoted to initialize the code, read input data and write results. For the computer cluster used in the PODIUM project the initialization time is around 30 s, and thus for this cluster the global simulation times cannot be reduced below this computational limit. Finally, to point out that even this limit can be easily reduced by using currently available computers, a Macbook Pro 13" from early 2015 (CPU: 2.7 GHz Intel Core i5, RAM: 8 GB 1867 MHz DDR3, SSD disc) has been tested and the corresponding initialization time was reduced to 10 s.

For MCGPU-IR, simulation times (use of GPU time) between 70 to 2 seconds have been tested. The absolute values obtained for a simulation time of 2 s agreed with those obtained for 120 s within statistical uncertainties (40%, $k=2$). However, it should be reminded that $Hp(10)$ is calculated by using only a few number of voxels at the detector position. The statistical uncertainty is much lower (< 1% in all cases) for the effective dose since most of sensitive organs are made of thousands of voxels. As mentioned before, the global simulation time is also dependent on the time devoted to initialize the code, read input data and write output data. For the computer cluster used in the PODIUM project the initialization time is around 60 s, and thus for this cluster the global simulation times cannot be reduced below this computational limit. However, when a complete realistic procedure has to be calculated, where tens to hundreds of irradiation events should be simulated, MCGPU-IR allows the user to simulate in one single run several irradiation events (up to 30) instead of running a separated simulation for each one. By using this batch technique, the simulation time of 30 events is reduced by a factor 1.3.

To conclude, it is worth mentioning that for PODIUM only 2 GPU cards were available running in our computer cluster, it is foreseen that when using a dedicated GPU cluster with more than two GPUs the computational times would be additionally reduced.

Conclusions

WP2 has provided a set of computational phantoms with a wide range of anatomies and postures. Thanks to the 3 female voxel phantoms and to the IPP tool, simulations could be performed which represent occupationally exposed workers and the real working scenarios that the PODIUM dosimetric approach was monitoring. On the one hand, we have made use of well-established female voxel phantoms from the HGMU family, which could serve as reference. On the other hand, we have made use of the more recently developed...
RAF phantom, which is flexible in his posture. We expect that with this variety of phantoms, we have made PODIUM’s approach to dosimetry not only more innovative, but also more individualized, for the benefit of accuracy.

Furthermore, WP2 has provided a library of pre-calculated fluence to dose conversion coefficients for phantoms having reference statures and non-reference postures as well as for phantoms having various statures that can be used as a first approach of the fast, online dosimetry application for workers in realistic workplaces. The numerical data of the conversion coefficients have been uploaded to the STORE database and can be found at DOI:10.20348/STOREDB/1156.

Two fast MC systems have been developed for its application in hospitals for interventional radiology procedures. The two tested codes provided acceptable results in simulation times that can be lower than 20 s (CPU/GPU use time) per simulated irradiation event.

It is worth mentioning that one of the main advantages of MCGPU-IR is the calculation of the effective dose, $E$, but this cannot be verified by comparison with dose measurements because physical detectors can only determine the operational quantities. The computing time required to calculate $E$ is much lower than to calculate $H_p(10)$ with this code. Likewise, when compared to PENELOPE/penEasy, MCGPU-IR offers the advantage to directly calculate $E$.

References
WP3: Development of the online dosimetry application

I. Goal

Within PODIUM several challenges were tackled such as staff tracking, definition of the workplace geometry, definition of the radiation source and calculation of the staff doses. But it was needed to combine all these developments in a way such that staff doses can be calculated by non-specialists in a user-friendly way. To do this it was required to develop a web application, the Dosimetry online Calculation Application (DCA), that connects with the different technical modules for staff tracking and dose calculation. The development of the DCA and the integration with the different technical modules was not straightforward and involved several challenges.

II. Main challenges

Firstly, it was needed to define the requirements for the DCA. Which functionalities should be included? How should the screens look like? How should the DCA interact with the technical modules? The requirements were defined at the beginning of the project and provided to the potential software developers. The main requirements are listed here:

- Each user should get an account with a profile, user name and password to login to the DCA. Different user roles should be foreseen with access to different screens and functionalities (monitored worker, procedure operator, radiation protection expert, dose calculator, manager).
- The main workflow was defined to be as follows:
  1. Creation of new procedure
  2. Connect with the Kinect camera
  3. Start the procedure and the tracking
  4. Pause/continue the procedure if necessary
  5. Stop the procedure and the tracking
  6. Enter the radiation field data
  7. Start the dose calculation
  8. Consult the calculated dose
- A front-end web application with user-friendly screens should be foreseen.
- A back end with databases and connection with external technical modules for tracking and dose calculation should be foreseen.
- The technical modules for tracking and dose calculation will be developed by the PODIUM partners, but they need to be connected with the DCA.

These requirements were then discussed with the different potential software developers. Based on flexibility and budget considerations, it was decided to hire the software developer Ariel von Barnekow through UPC for development of the DCA.

During the actual development the biggest challenge was to align the teams working on the different technical modules. The input and output data and the data format need to be consistent between the different modules in order to integrate them with the DCA. Furthermore, also translating from what the scientists want to what the software developer can implement involved quite some effort.

III. Technical aspects

The technical aspects of the software will not be discussed in detail, as this is outside the scope of this report. The development of the DCA and the integration of the technical modules required the use of a large variety of different technologies. An overview of the used technologies is shown in figure 3.1. The structure of the
software is shown schematically in figure 3.2. The users interact with the DCA through the web application. The DCA and the corresponding database are hosted on a dedicated server at UPC together with an API for runner authentication and for retrieving data from and uploading data to the database. The runners for the dose calculation modules are running on a separate server at UPC. Computationally demanding calculations can be run through Secure Shell Connection (SSH) on the UPC computer cluster. The runners for the staff tracking run on a local computer at the workplace. The communication of the web application, the dose calculation server, the tracking server and the computer cluster with the DCA server goes through Hypertext Transfer Protocol Secure (HTTPS).

Figure 3.1: Technologies used for the development of the DCA and the integration of the technical modules

Figure 3.2: Schematic representation of the software architecture
IV. General process flow

Before using the DCA, the different components need to be correctly installed at the site where it will be used. The motion tracking module needs to be installed in the room where the radiation source is installed. This is an external module that will run locally, but will communicate with the DCA web application. The dose calculation module can be installed locally or can run on a remote cluster. This is also an external module that will communicate with the DCA web application. The DCA web application itself can be accessed by login in through the browser. If no internet is available on site, it is also possible to install it locally.

The DCA is based on different user roles, each with its particular responsibilities and possibilities: Monitored Worker (MW), Procedure Operator (PO), Image Processing Expert (IP), Dose Calculator (DC), Radiation Protection Expert (RP), Manager (MG). It is possible to combine different roles in a single user. The responsibilities and possibilities for each role are listed in table 3.1.

For each user the manager needs to create a user account with the appropriate role(s). The user can then login to the DCA web application by using its username and password. Once logged in, the user will see the dashboard with some basic guidelines and all the features available for his role(s) (see figure 3.3). The user also has to possibility to change his profile (personal information, password, language, …).

Table 3.1: Responsibilities and possibilities of the different roles in the DCA

<table>
<thead>
<tr>
<th></th>
<th>MW</th>
<th>PO</th>
<th>IP</th>
<th>DC</th>
<th>RP</th>
<th>MG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Login</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Modify profile</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Modify preferences</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Be tracked</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>View own doses</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3: Screenshot of the DCA dashboard for a user with all the roles activated
Before a procedure can be started, the workplace (C-arm, protective equipment, ...), procedure type and worker data need to be defined. Also the tracking system and the dose calculation system need to be connected to the DCA web application. These are the tasks of the manager.

If all these data are available and the connections with the tracking and dose calculation systems are ready, a procedure can be created by the procedure operator. He has to provide the specifications of the procedure, room, patient and monitored worker (see figure 3.4). Once the procedure has been created, the procedure operator can connect with the tracking system and start the procedure and the tracking (see figure 3.5). If necessary the procedure can be paused and resumed. Finally, the procedure operator can stop the procedure. The tracking file will then become available. The RDSR file containing the radiation source data has to be uploaded manually by the procedure operator because direct communication with the C-arm is not possible yet.

![Figure 3.4: Screenshot of the DCA procedure creation screen](image-url)
Once a procedure has finished and the tracking and RDSR files are available, the dose calculator can go to the overview of the procedures and start the dose calculation (see figure 3.6). The dose calculator can select the desired dose calculation method from the dropdown list. It is possible to calculate the doses with multiple methods. Once the dose calculation is finished, the dose file will also become available. Once the procedure and the dose calculation are finished, the doses can be consulted by the monitored worker (only own doses) and the radiation protection expert (all workers on his site). The dose detail screen gives the procedure information, the dose calculation method and the calculated doses (see figure 3.7).
Figure 3.6: Screenshot of the DCA procedure dose calculation screen

Figure 3.7: Screenshot of the DCA dose details screen
V. Current limitations and outlook

The different features of the DCA were tested by test cases in hospitals. However, as the DCA and the tracking and dose calculation modules were still under development during the project, these tests were always partial. Therefore, it is planned to test now the complete process flow with the final version of the DCA and the tracking and dose calculation modules by tracking staff in interventional radiology in Belgian and Swedish hospitals after the project. But no big issues are expected here because of the previous partial tests.

The DCA developed during the PODIUM project is a prototype to proof the feasibility of the PODIUM approach. In the future the functionalities of the DCA can be extended in different ways:

- Currently, the DCA is targeted towards the use in hospitals for interventional radiology. In the future the DCA should be extended towards other user cases such as neutron workplace fields. The DCA is made in a modular way such that its use can in the future be extended towards other applications relatively easily.
- Currently, the DCA does not yet calculate doses in real-time. The problem is that the data from the X-ray console cannot be obtained in real-time. Therefore, the X-ray data need to be uploaded manually after a procedure using the RDSR file and only then the dose for the procedure can be calculated. By collaboration with manufacturers it should be investigated how direct communication with the X-ray system can be established. This will then also allow moving towards real-time dose calculation.
- Currently, the doses can be consulted by clicking on the procedure of interest. However, for the future it would be useful to have data grids with filters and graphs to allow more detailed investigation of worker doses over time.

VI. Conclusions

The goal of WP3 was to develop a user-friendly application that combines all the developments made within the PODIUM project and allows non-specialist users to assess and follow up staff doses.

A set of requirements was listed for this application and a software developer was hired through UPC to develop the so-called Dosimetry online Calculation Application (DCA). The technical modules for staff tracking and dose calculation were developed as external modules by the PODIUM partners. However, they had to be connected with the DCA.

The DCA was successfully developed in accordance with the predefined requirements. The external modules for staff tracking and dose calculation were also successfully developed and integrated with the DCA. Users work with the DCA by logging in to a user-friendly web application. Each user has its predefined roles. The whole process flow is implemented in a logic and easy to follow way. First room, radiation source and worker data have to be inserted in the database. Then a procedure can be defined and created. Once connection with the locally installed tracking system is made, the procedure can be started. After finishing the procedure the tracking file is uploaded automatically by the tracking system. The RDSR file containing the radiation source data has to be uploaded manually because direct communication with the C arm is not yet possible. Then the dose can be calculated with the dose calculation method of interest by connecting with the locally or remotely installed dose calculation system. Finally, the radiation protection expert and workers can consult the calculated doses.

The DCA was already successfully tested in clinical practice. The first tests were always partial because the DCA was still under development. However, more testing in clinical practice with the final DCA version is ongoing. Some future improvements are possible, but with this version of the DCA the goal of WP3 is already reached. Furthermore, it proofs the feasibility of the PODIUM approach.
WP4: Assessment and validation of the online dosimetry application in hospitals

4. Validation of the on-line system in interventional radiology

The main aim of this part of the project was to perform a proof-of-concept of the online dosimetry application in hospitals, in particular in an interventional radiology setting. In order to accomplish this, the work was divided into three main tasks. The online application was tested in an experimental set-up using clinical X-ray equipment and tests were performed during actual patient treatments. Furthermore, the future development needs were identified.

4.1 Initial validation in a controlled experiment set-up in a hospital

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 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. In addition, staff move out of the room during image acquisition, and this differs between rooms and procedures. The prerequisites for using radiation protection techniques, e.g. ceiling mounted radiation shielding differ. The calculations are thus challenged by the actual variations that occur across different hospitals, clinical rooms and procedures.

Validation includes verification of the simulated values and items affecting the acceptability of the systems to be introduced in the hospital. From the early planning stages of the PODIUM project, it was important to ensure that the system was tested under exposure situations that were relevant across a range of interventional radiology/cardiology settings. The radiation source (fluoroscopic X-ray system) should be broadly similar to that found in a typical modern hospital environment. For this reason, two hospitals were chosen as the clinical validation sites; Skåne University Hospital, Malmö, Sweden and St. James’s Hospital (SJH), Dublin, Ireland. Both hospitals are equipped with modern interventional angiographic flat-panel detector (FPD) X-ray systems. Both hospitals are large, teaching hospitals with busy workloads. Procedures may be carried out by relatively large numbers of staff in the room. This is relevant as the outcome is challenged by complex installations where there is much equipment and many staff members to track.

The clinical cases were chosen based on procedures that were commonly performed around Europe, and where there was also reference dose data available in the scientific literature. Endovascular Aortic Aneurysm Repair (EVAR) and other vascular procedures performed typically by Vascular Surgeons were selected, along with Coronary Angiogram and Percutaneous Coronary Intervention (PCI) procedures performed in a Cardiac Catheterisation laboratory by Cardiologists. A description of the installed base of equipment that was chosen for the validation is shown below in Table 4.1.

**Table 4.1 Equipment used for PODIUM clinical validation.**

<table>
<thead>
<tr>
<th>Hospital</th>
<th>Room</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Age of Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skåne University Hospital, Malmö</td>
<td>Vascular room No. 105</td>
<td>Siemens</td>
<td>Artis Zee</td>
<td>2 years old</td>
</tr>
<tr>
<td>SJH, Dublin</td>
<td>Endovascular Theatre</td>
<td>Siemens</td>
<td>Artis Q</td>
<td>4 years old</td>
</tr>
<tr>
<td>SJH, Dublin</td>
<td>Cardiac Cath Lab 2</td>
<td>Philips</td>
<td>Allura FD10-10 Bi-plane</td>
<td>5 years old</td>
</tr>
</tbody>
</table>
The IT aspects of the online tool were also considered and aspects of this proved to be a challenge. In each room, it had to be carefully considered where the motion-tracking camera (Microsoft Kinect™) (with cables) and PC or laptop (to operate it) would be placed. Power and network points had to be identified. For use in the operating theatre, the preferred solution is a medical grade PC. The minimum operating requirements for PODIUM are now detailed in the user manual for the IPS and must be verified locally before starting to install the system. The file size of tracking files was also considerable, therefore storage and backup requirements should be taken into account and efforts made to minimized the amount of data collected where possible.

### 4.1.1 Operator positioning data

The basic performance of the chosen IPS system, the Kinect 2.0, has been extensively evaluated as this is a commercially available product and used for a variety of applications. The basic features were also evaluated in the available labs in Spain, Belgium and Sweden. The experimental set-up from one of these tests are shown figure 4.1. The goal was to investigate and verify that the given distance from the IPS to the person is accurate when compared to the actual measured position in the X-ray lab. The position from the IPS to the upper part of the body was measured using a laser measuring tool (Bosch GLM 100 C) and compared with the result from the IPS. The result presented in table 4.2.

![Figure 4.1](image.png)

**Figure 4.1** A schematic sketch of the distance IPS to operator measurements. The three measurement points are shown.

**Table 4.2** The result of the distance measurements.

<table>
<thead>
<tr>
<th>Given distance [cm]</th>
<th>Measured distance [cm]</th>
<th>Deviation [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>302.6</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>383.2</td>
<td>3.7</td>
</tr>
<tr>
<td>3</td>
<td>418.6</td>
<td>10.2</td>
</tr>
</tbody>
</table>

These and other tests conclude that the distance measurements of the IPS is sufficient for tracking the movements of an operator working 1 – 5 meters in front of the camera and with an approximate total accuracy of approximately +/- 10 cm when measuring points at the upper body. One has to note that the measurement point was on the surface of the body not the midpoint in the body. This may influence the result of the calculations. Positioning of the IPS to avoid occlusion is important. In a typical clinical x-ray room multiple objects and
equipment can block or partially block the view of the camera. For example, the X-ray equipment, (primarily the large C-arm components) could block the view, as well as the ceiling mounted monitors. The ceiling mounted radiation protection equipment could also block the view of the operator. Both the c-arm, the monitors and the radiation shielding can be moved and are frequently moved during patient investigations. The first experiments in the Belgian hospitals confirmed that the real-time tracking performance was feasible and the tool was able to track the simulated actions of an operator. The tracking skeleton was correctly overlaid on the RGB image for the majority of the case. The tracking was not hindered by the movable ceiling shield because it was transparent enough to the infrared beam. However, the performance is very much dependent on the position of the IPS in order to locate and track the operator fully. The frontal view was important in order to track hand movement. It became clear that for each interventional room, an optimal position will need to be determined, because there can be important differences between rooms.

Installing the IPS and the associated software introduced a number of issues. Several placements were tested firstly in an interventional room in Belgium with a trial and error method. Whereas in Belgium, one preferred position was on the large TV 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 each option resulted in many clinical difficulties. It was concluded that is not easy to determine a suitable position without a detailed knowledge of clinical practice.

The staff are wearing personal protective equipment (PPE) such as surgical gowns, face mask, gloves, head caps and lead aprons) and this could affect the tracking. The early investigations revealed that the protective clothes used did not hinder the tracking. Significant jittering movement or oscillation when tracking of the legs was observed due to the fact that the legs were hidden under the lead apron. The conclusion from these measurements was that the legs have to be assumed to follow the movement of the hips’ joints.

The experiments confirm that the primary person of interest for the PODIUM validation (the main operator) was given a tracking ID when moving around the patient. The output data for the tracked position from several body parts (the trunk of the operator, the head of the operator, the hands of the operator) was generated with an acceptable accuracy. The output database contains the tracked position of all monitoring data from the staff. The virtual phantom for the simulations will be assumed to be “positioned” at these data points.

The light is dimmed in some of the procedures which was not an issue as the IPS uses infrared for the depth estimation.

It was observed that if two doctors perform the procedures, the tasks can be exchanged between them which makes the tracking considerably more difficult. In addition, the doctor(s) could leave the field view several times. This can occur while the radiation beam is off and also while the radiation beam is on, if they step back as is good practice during higher dose digital acquisition runs.

The key criteria for the position of the Kinect camera was to avoid occlusions as much as possible, and to maintain good accuracy of depth estimation:

- The camera should have a frontal view of the operator
- The camera should be located between 1 and 5 meters from the tracked users of interest
- The camera position needs to be fixed i.e. not moving during the acquisition
- The camera location needs to be known in the room world coordinates to correctly transform the coordinates from the camera space to a reference point

In a real clinical situation the tracking is also challenged by the fact that the doctor could switch between the sides of the bed in some procedures i.e. operating from the left side of the patient instead of from the right side which means that there is no frontal view of the operator. This can be a limiting factor for some clinical applications with a one camera system.
Also, 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. If this is not considered, the possibility exists that the main operator and another staff member responsible for the occlusion swaps tracking ID, and PODIUM would not simulate representative dose values. The validation in the clinic was performed for the main operator only, but the Kinect will track any person in the field of view which may be 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 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 Kinect 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, noting that facial recognition is not possible during procedures when face protection such as surgical masks are used.

The early experiments showed that the 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. 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 and this can be a major problem.

The Kinect produces data with reference to the Kinect camera. This is not directly useful for the simulation calculation software and correlation with the geographical positioning of the scattered radiation is needed. A calibration of the IPS in the clinic is needed. Furthermore, the correlation of the 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 needed. During our measurements this has been performed manually in some hospitals, and in others it was possible to synchronize the systems to an NTP server (see 4.1.4). 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 output data from the IPS 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 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. In the future, this issue could be solved by just storing the data when the beam is on.

### 4.1.2 Radiation source specific data

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 specifying the
scattered radiation include the following: 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. These parameters are technical parameters from the x-ray machine and retrievable. The scattered radiation is also specified by the source to detector distance, radiation field area, thickness of the exposed body, attenuation in the couch and mattress. The thickness of the exposed body could be assessed knowing the weight and length of the patient. The attenuation in the couch is not readily available in the clinical report, but can be experimentally estimated or may be available from the manufacturer. The dose area product (DAP) or air-kerma in the reference point are used in the simulations and should also be retrievable and checked for accuracy.

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, but this is in reality not always the case. Moreover, vendor specific and user specific data could also be included. The system must be able to extract data from any supplier and the differences can make data management more difficult. 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.

Figure 4.2 gives a schematic overview of data sources that could contain important data. 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.

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. During the validation, it was also noted that the extraction was set-up differently for different x-ray machines and the data needed was therefore not readily available.

The age of the equipment is of relevance. A key factor needed for the system is the easy availability of an RDSR as defined by the DICOM Standard. These reports include metrics such as Dose Area Product (DAP), as
Deliverable D1.121

well as detailed geometric and technique information. RDSR outputs are required for interventional fluoroscopic equipment conforming to IEC 60601-2-43 (2nd edition 2010) and therefore they may not be available on older systems. An RDSR contains data on every event on the X-ray system, i.e. every time the foot-pedal or exposure button is pressed; a unique event is created containing a wealth of information on the X-ray primary beam conditions, table positions, angulation and collimation, to name a few recorded parameters. This file of exposure conditions (with a timestamp) is combined with the positional information of the staff member (at the same timestamp) and used in the simulation Monte-Carlo software to simulate the scattered radiation at that time and position, therefore the RDSR file is a mandatory item needed for the Monte-Carlo simulation.

The data could vary for different types of x-ray machines settings, different treatments and different patients. The variation between different patients and/or treatments types is significant. Data from room 105 at the Skåne University hospital in 2018 was investigated. Over 4000 irradiation events from 41 treatments are shown in Figure 4.3 – 4.6. 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.

![Image of tube angulations](image1)

**Figure 4.3** The different tube angulations used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö. Variation of angulation of the x-ray machine summarized for several treatment.

![Image of tube voltage](image2)

**Figure 4.4** The different tube voltage used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö.
It is evident that data used as input to the simulation have great inter and intra treatment variability. It is important to identify which data have the most impact on the simulation result.

Immediate collection of data from the x-ray machine is needed. The file is stored with a defined standard and format (.SR), it can be converted into other file formats and the contents can vary (examples in Figure 4.7 and 4.8 below).

Understanding the format and contents of different RDSRs and determining the key factors needed for PODIUM was another challenge. In order to overcome some of these differences and to obtain files from different systems in a standard format, as part of WP3, a software tool was developed to allow for RDSR files to be (i) anonymized (ii) exported to different file formats and (iii) matched with tracking files from the IPS Kinect camera. This convenient tool is available for different versions of Windows operating systems (32 bit and 64-bit) and has been tested locally on the hospital IT systems used in PODIUM.

Some manufacturers systems that were used in the validation include fields that are not present in other systems. When this was the case the information had to be recorded manually or estimated. Some typical

---

**Figure 4.5** The different added tube filtration used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö.

**Figure 4.6** The different radiation field area used for 4000 different consecutive machine exposures during three months from operating room 105 in Malmö.
items that were found to be missing or incomplete were the field size, and the horizontal movement of the C-arm. It was a challenge for the project team to become fully familiar with the format and contents of different RDSRs.

![Figure 4.7 An example of RDSR file in .XLS format.](image)

![Figure 4.8 Example of RDSR file in .DCM format.](image)

4.1.3 Other data important for the simulation and preparing the data for calculations

The radiation personal protective equipment (PPE) as well as the radiation protection equipment available in the room, have a great impact on the staff dose. Including this in the calculations is essential. However, protective equipment has not yet been included in the calculations. This makes the comparison with the measurements more difficult.

Also another issue, the synchronization of the radiation source equipment with the IPS software tool (e.g. clock setting on the hospital PC used for PODIUM) was not fully solved in time for the verifications in the project. The simulation depends on taking each irradiation event and matching this (with an accuracy of 1 second) to the file tracking the position of the staff member. In the first validation experiments, some
discrepancies were noted, and a correction in terms of minutes and seconds was made to every irradiation event. In Malmö this was not solved and the time stamps had to be corrected manually. However, subsequently in SJH, each vendor was asked to set their X-ray machine PC time to an NTP server which the hospital uses for all hospital PCs. This can solve the problem of correcting for any discrepancies and ensures that both clocks used for the project are synchronized to the greatest possible degree of accuracy.

4.1.4 Sensitivity measurements

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, Sweden) placed under the table couch at 89 cm. The measured air-kerma was recalculated to the x-ray system reference point at 108 cm above the floor. Measurements were performed for two different gantry angles (0°, 15°). The detector was also placed on the anthropomorphic phantom (CT Torso Phantom CTU-41, Kyoto Kagaku, Japan) chest mimicking the main operator, at two different operator positions. To generate scatter radiation another anthropomorphic phantom (Adult ATOM® Dosimetry Verification Phantoms, Cirs, USA) was placed on the table of the X-ray machine, acting as patient. Additional eye dose measurements were performed with Educational Direct Dosimeter (EDD-30) (Unfors, Sweden). The setup is shown in Figure 4.12.

![Figure 4.9 The experimental set-up for a basic sensitivity test.](image)

The results of the measurements are presented in Table 4.3. The given dose quantity is kerma-air. The values for the reference point given in the RDSR-file and the 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 approximately 2-3 %, which is much lower than the required accuracy in personal dosimetry.

Table 4.3 The result of the basic sensitivity measurements.

<table>
<thead>
<tr>
<th>Meas. position</th>
<th>X-ray tube angulation</th>
<th>RSDR Ka ref, µGy</th>
<th>Meas. Ka ref, µGy</th>
<th>Phantom Chest Ka, µGy</th>
<th>Phantom eye Hp(3), µSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>860</td>
<td>880</td>
<td>0.76</td>
<td>0.48</td>
</tr>
<tr>
<td>1</td>
<td>15°</td>
<td>880</td>
<td>891</td>
<td>1.25</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>0°</td>
<td>860</td>
<td>880</td>
<td>0.08</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
<td>880</td>
<td>891</td>
<td>0.11</td>
<td>0.42</td>
</tr>
</tbody>
</table>
For the 15° angle measurement, with the beam aimed away from the operator, the doses from scatter radiation are higher for both Pos 1 and Pos 2. 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 1 to pos 2, 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.

### 4.2 Verification of calculated values in the controlled experiment set-up in a hospital

Two measurements in the experimental set-up were performed. The phantom simulating the patient was irradiated at chest area. In the first measurements, the x-ray tube was positioned from 0-degree straight below the phantom and the other measurement was performed with a 15-degree angle (the x-ray tube is move at opposite side as the operator (phantom) is positioned. All machine parameters were extracted from the RDSR file generated during the exposures (Table 4.4). The ceiling mounted lead protection was not used.

**Table 4.4** Summary of some basic data used in experiments.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>kVp</th>
<th>Filtration mm Cu</th>
<th>KAP Gycm²</th>
<th>Ka mGy</th>
<th>Field size cm²</th>
<th>Angulation (prim °)</th>
<th>Focus – detector distance mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>79</td>
<td>0.3</td>
<td>4.1</td>
<td>10.4</td>
<td>835</td>
<td>0</td>
<td>1199</td>
</tr>
<tr>
<td>2</td>
<td>79</td>
<td>0.3</td>
<td>4.2</td>
<td>18.0</td>
<td>835</td>
<td>15</td>
<td>1199</td>
</tr>
</tbody>
</table>

**4.2.1 Material and methods**

On the patient couch, a CIRS Phantom (Adult Male Phantom Model NO. 701, USA) was placed simulating the patient. Measurements of Hp(10) using TLD (type TLD 2000C (Li:Mg,Cu,P), Thermo, USA) and Electronic Personal Dosimeters (EPD) (Thermo Mk type, Electron, Thermo Fisher Scientific Inc, USA). The uncertainty of the TLDs is of the order of 10% (k=1) for doses above 70 µSv. This value is calculated considering the uncertainty associated with the repeatability, energy and angular response for the energy range of interest. The uncertainty of the EPD reading is of the order of 10% (k=1) according to the manufacturer information, considering energy and angular response and the accuracy for Cs-137.

The main operator was mimicked using a CT Torso phantom CTU-41 (Kyoto Kagaku, Japan). The detector (R100 dose probe RTI, Sweden) was used for the measurements in the radiation field.

The position of the dosemeters for each measurement are given below in figure 4.10. All necessary distances were measured in order to get the distance from the isocenter to the dosemeters.
The selected Monte Carlo calculation codes used in PODIUM was used in this experimental set-up: PENELOPE/penEasyIR, MCGPU-IR, MCNPx, as well as, IPP-SE, the software based on the look-up table approach. The output values from the simulations was $H_p(10)$. The look-up table approach also provides estimates for effective doses, (peak) skin doses, eye lens doses.

The statistical uncertainty in the calculations using PENELOPE/penEasyIR, MCGPU-IR or MCNPx is below 2.5% ($k=1$). In addition, the uncertainties associated with the KAP or Kref value used in the normalization was estimated. This uncertainty is estimated from quality control surveys and is taken equal to 10% ($k=1$). The uncertainty using the look-up table approach IPP_SE is at least 10% due to the use of KAP as an input value. The uncertainty in the position of the operator is not included in the uncertainty given.

The simulation time was 120 s per event for Penelope/penEasyIR, 111 s per event for MCNPx and 40 s per event for MCGPU-IR. IPP_SE the total execution time was about 10 seconds for both measurements. Due to the fixed positioning of the dosimeter on the chest of the phantoms, the result from simulations using IPP_SE, is only comparable to the dose measured with the EPD1 dosimeter.

### 4.2.2 Results

Table 4.5 shows the simulated $H_p(10)$ and measured $H_p(10)$ for the two experiments.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EPD1</td>
<td>73 ± 8</td>
<td>84 ± 9</td>
<td>80 ± 9</td>
<td>90 ± 10</td>
<td>89</td>
</tr>
<tr>
<td>EPD2</td>
<td>72 ± 8</td>
<td>80 ± 8</td>
<td>56 ± 6</td>
<td>80 ± 9</td>
<td>-</td>
</tr>
<tr>
<td>DC52</td>
<td>134 ± 13</td>
<td>94 ± 9</td>
<td>75 ± 8</td>
<td>110 ± 12</td>
<td>-</td>
</tr>
<tr>
<td>DC48</td>
<td>85 ± 8</td>
<td>72 ± 7</td>
<td>96 ± 10</td>
<td>82 ± 9</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EPD1</td>
<td>73 ± 8</td>
<td>56 ± 6</td>
<td>54 ± 6</td>
<td>77 ± 9</td>
<td>51</td>
</tr>
<tr>
<td>EPD2</td>
<td>63 ± 7</td>
<td>50 ± 5</td>
<td>40 ± 4</td>
<td>60 ± 7</td>
<td>-</td>
</tr>
<tr>
<td>DC36</td>
<td>103 ± 11</td>
<td>65 ± 7</td>
<td>61 ± 7</td>
<td>78 ± 9</td>
<td>-</td>
</tr>
</tbody>
</table>
The MCNPx seems to give the highest simulated values. The ratio between the measured and simulated value was also calculated and presented in figure 4.11.

These experiments involved phantoms only and the first case to verify the output of the Monte Carlo simulation. All relevant parameters are known, as they were measured and controlled during the procedure. The limitation of this case is that it does not include tracking of operator movement or use of radiation protection equipment.

The ratio between the simulated and measured values varied between 0.77 and 1.15 for PENELOPE/penEasyIR and 0.63 and 1.10 for MCGPU-IR, 0.95 and 1.23 for MCNPx and 0.82 and 1.42 for IPP_SE. As regards the comparison with the 3 TLDs, the ratios are in the same magnitude. The ratios are in the same range for the four simulation techniques, and reasonable considered the uncertainties.

The difference of the actual position of the dosemeter, the real world coordinates of the dosimeters, in relation to the scoring point in the Monte Carlo simulations may influence these differences. Changing 5 cm the position of the scoring point in the Monte Carlo simulation can produce a 10% difference in the dose. The uncertainty in the positioning of the operator is not included in the uncertainties given.

4.3 Validation of the application during patient treatments in the hospital
The verification measurements were performed at the Skåne University Hospital (LU) and St James´s Hospital (SJH). The cases were named LU6 and LU7 for the procedures were carried out at Skåne University Hospital and the SJH C and SJH1 were at St James´s Hospital.

4.3.1 Methods and material
A description and results from the measurements are followed by a description and results of the simulations. Table 4.6 summarizes for measurement and Table 4.7 summarizes the simulations performed. It should be noted that for two of the treatments LU 6 and SJH 1, the ceiling mounted radiation protection was used. This protective shielding was not included in the simulations. This should mean that the measured dose give much lower values compared to calculations for LU and SJH.
Table 4.6 A summary of the clinical cases included in the report.

<table>
<thead>
<tr>
<th></th>
<th>LU 6</th>
<th>LU 7</th>
<th>SJH C</th>
<th>SJH 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procedure</td>
<td>Renal artery angiography</td>
<td>Angiography leg</td>
<td>Angioplasty with iliac stenting</td>
<td>PCI</td>
</tr>
<tr>
<td>Ceiling shielding used</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sim of shielding</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Measurement</td>
<td>On abdomen</td>
<td>Chest left pocket</td>
<td>Chest left pocket</td>
<td>Chest right</td>
</tr>
<tr>
<td>Dosemeter</td>
<td>Mirion DMC 3000</td>
<td>Raysafe i2</td>
<td>Thermo Mk</td>
<td>Thermo Mk</td>
</tr>
<tr>
<td>Irradiation events</td>
<td>186</td>
<td>19</td>
<td>67</td>
<td>163</td>
</tr>
</tbody>
</table>

Table 4.7 A summary of used calculation for the different cases.

<table>
<thead>
<tr>
<th>Dose calculation</th>
<th>LU 6</th>
<th>LU 7</th>
<th>SJH C</th>
<th>SJH 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>PENELLOPE/penEasyIR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MCGPU-IR</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>MCNPX</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>IPP_SE</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Effective dose was also calculated for LU 7 and SJH 1 using IPP_se and the three phantom, RAF, Donna and Irene.

The following figures 4.12 – 4.15 schematically show the measuring point and the point for which the dose was calculated for each case included in this report. It should be noted, that the dosemeters were positioned over the lead apron of the operator and the simulations did not take the lead apron into account either. The measurement value from the dose meter 2, figure 4.12, was used in the comparison with simulations for LU 6.

Figure 4.12 Schematic views of the measuring and calculations points for the procedure LU 6.
Figure 4.13 Schematic views of the measuring and calculations points for the procedure LU 7.

Figure 4.14 Schematic views of the measuring and calculations points for the procedure SJH C.

Figure 4.15 Schematic views of the measuring and calculations points for the procedure SJH 1.

The simulation time per event is presented in table 4.8.
The fastest calculations are performed by MCGPU-IR. The other three applications were about the same speed for these calculations.

### 4.3.2 Results

A summary of the measurements performed in Malmö and Dublin is shown in tables 4.9a and 4.9b. In table 4.9a the simulations are compared with the measured values.

#### Table 4.9a A summary of measured and calculated dose for all cases.

<table>
<thead>
<tr>
<th>Hp(10) µSv</th>
<th>LU 6</th>
<th>LU 7</th>
<th>SJH C</th>
<th>SJH 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>30 ± 6</td>
<td>0.25 ± 0.05</td>
<td>55 ± 11</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>PENELOPE/penEasyIR</td>
<td>50 ± 5</td>
<td>0.53 ± 0.05</td>
<td>22 ± 2</td>
<td>670 ± 67*</td>
</tr>
<tr>
<td>MCGPU-IR</td>
<td>25 ± 3</td>
<td>0.25 ± 0.03</td>
<td>-</td>
<td>252 ± 28</td>
</tr>
<tr>
<td>MCNPX</td>
<td>35 ± 4</td>
<td>-</td>
<td>48 ± 5</td>
<td>655 ± 97</td>
</tr>
<tr>
<td>IPP_SE</td>
<td>-</td>
<td>1.52 ± 0.3</td>
<td>59 ± 12</td>
<td>-</td>
</tr>
</tbody>
</table>

* the central point and shoulder point of simulation are given (fig 4.15).

In table 9b, the simulated Hp(10) using the IPP_SE code is compared with the simulated effective dose (E) using different the RAF, Donna and Irene phantoms. It should be noted that Hp(10) was estimated for an over the lead apron position and the effective dose is assessed with the lead apron on the phantom.

#### Table 4.9b Effective dose and Hp(10) calculated for LU7 and SJH C.

<table>
<thead>
<tr>
<th></th>
<th>LU 7 Hp(10) µSv</th>
<th>LU 7 E µSv</th>
<th>SJH C Hp(10) µSv</th>
<th>SJH C E µSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPP_SE RAF</td>
<td>1.52</td>
<td>0.15</td>
<td>58.94</td>
<td>14.03</td>
</tr>
<tr>
<td>IPP_SE Donna</td>
<td>1.35</td>
<td>0.06</td>
<td>57.75</td>
<td>3.95</td>
</tr>
<tr>
<td>IPP_SE Irene</td>
<td>1.35</td>
<td>0.13</td>
<td>57.75</td>
<td>8.65</td>
</tr>
</tbody>
</table>

The most obvious observation is the large discrepancy in the measured vs simulated Hp(10) for SJH 1 which would be expected because the the radiation shielding used during the case was not included in the simulations. However, for LU 6 no such discrepancies could be observed and the small differences between measured and calculated Hp(10) for LU 6 were not expected. This is somewhat inconsistent and difficult to explain. However this could be due to different positioning of the shielding with respect to the operator.

The comparison between measured and calculated Hp(10) is most straightforward for LU 7 and SJH C for where the ceiling-mounted shielding was not used. For LU 7, the simulations results in both higher and lower values compared to the measured value, depending on the method used. For SJH C, the simulated values for MCNPx and IPP_SE are well in line with the measured value, but when using penEasyIR, the calculated and measured values deviate by a factor of 2.
The simulated Hp(10) using IPP_SE and different phantoms simulating the operator gave similar results as expected. However, the effective dose calculation gives similar results using the different phantoms for LU 7 but for SJH 1 the discrepancy is much larger. It should be noted that the level of Hp(10) and effective dose could not be compared due to the fact that Hp(10) gives a value over the lead apron and the effective dose take the lead apron into account.

It is not only important to compare the results between measured and simulated values, it is also valuable to compare the different simulation methods. The comparison is influenced by several factors. One that affects the measured dose, and which is difficult to evaluate, is the shielding of the dosemeters from body postures. It is possible that the dosemeter in several operator positions is shielded by e.g. left arm. Such effect on the measured value can be significant. This a other parameters affecting the final result have that has to be analysed more in detail.

The non-homogeneous scattered field is also a parameter that contributes to the difficulties when comparing the results. If the dosimeter and the position of the simulation point differ, the measured and simulated dose could differ significantly as well.

4.4 Future improvement needs identified

4.4.1 Improvements of input data

- Accessibility to data from the x-ray system

A key input needed for PODIUM is the easy availability of an RDSR as described in section 4.1.2. Therefore, a limitation of the PODIUM system is that it will only be compatible with modern systems capable of producing an RDSR. On systems where an RDSR is available, it was also found to be a challenge to extract it from the system. Therefore access to an RDSR may not be straightforward for many users of interventional systems. Once an RDSR is available, even though it is a file with a defined standard and format, the contents can vary. For example, in some cases the field size was missing. In addition, the horizontal movement of the C-arm (along the length of the patient) is tracked or displayed in the real-time by the vendor but not usually stored in the RDSR. This position is relevant for determining the scatter source position in simulations and is discussed again below in relation to the global co-ordinate system.

Overall a considerable amount of time and effort was spent on understanding the format and contents of different RDSRs and determining the key factors needed for PODIUM was another challenge. Much work was done in tandem with WP3 to develop software tools to manage this.

- Defining the global co-ordinate system

The need for a global co-ordinate system for a specific operating room has also been noted and it is important to continue to simplify and automate measurements required for this system. This may require close work with X-ray machine vendors in the future to explore live links to their systems. This would allow for the transfer of positional information that may be present in the system but that is not currently stored in the RDSR (e.g. the position of the table is typically included, but not necessarily the position of the C-arm).

- Identification of the persons-of-interest

The PODIUM indoor position system (IPS) was first developed as a single camera system. It was observed from early tests that, in a busy clinical room with much equipment and with several staff members moving around the room, occlusion is clearly an important issue. This may lead to an incorrect skeleton representation of the operator. If a staff member is partly occluded by the C-arm, by another staff member, or if they are not facing the camera to be ‘picked up’ by the software, the tracking software will find it difficult
to represent their skeleton co-ordinates correctly. In the validation measurements, efforts were made to minimize this problem by mounting the Kinect on the TV monitor in the room where occlusions were less of a problem and a clear direct view of the main operator was feasible for most of the case. In some cases where the two operators were very closely working together the system can overlap and work has been done to improve this separation of staff members. In addition, for clinical reasons and patient access, in some cases staff will stand on the opposite side of the table to that where the Kinect is pointed. For these cases they are untracked and totally out of the field of view. For these reasons, a multi-camera solution is the preferred solution and a considerable amount of work was carried out towards the latter part of the PODIUM project to develop a 2-camera system and initial calibration and validation tests have been completed with this system.

- Identification and simulation of objects, including ceiling mounted lead shielding

As described above, the system does not function well when there are are radiation protection features such as a lead-glass shield, or the table-side shielding that cannot be easily tracked with the Kinect. During the validation, efforts were made to track the position of the ceiling screen by an observer who could describe the typical setup and provide sample or representative photos of the setup. In addition, a more quantitative approach was tested using small IMU Meta Motion devices to send gyroscope information via Bluetooth. The automated tracking of the lead-glass shield is one limitation that will need to be addressed for future versions of the application.

4.4.2 Improvements of output data

In this project, the main focus was on the estimation of the personal dose equivalent, Hp(10). Given the timescale of the project, to a lesser extent, the effective dose and organ dose were assessed. For the clinical validation measurements, staff were typically asked to wear active personal dosimeters (APDs) with instant read-out, worn over the lead apron and giving a result in Hp(10).

For the validation purposes passive eye (Hp(3)) and finger (Hp(0.07)) dosimeters were proposed to assess eye and finger doses. Staff were willing to participate in wearing the eye dosimeters with no concerns. There was more reluctance regarding the wearing of extremity or ring dosimeters as staff were concerned about the sterility of the rings and fitting them neatly under their surgical gloves. For this reason, ring dosimeters were not used for the validation measurements. The difficulties measuring finger dose highlights another possible benefit to the PODIUM approach, where finger dose can be calculated without the need to wear dosimeters that may be a burden for staff. Passive eye dosimeters were issued for single cases only. In many cases, the low doses for one uncomplicated procedure could not be measured and therefore could not be compared with the PODIUM simulations. This also highlights the benefits to the PODIUM approach, whereby the risk of losing doses from lost physical dosimeters is eliminated, and it may be possible to simulate the dose from very low dose cases.

So far, only the Hp(10) measurements have been used in the validation but in the future assessment and validation of eye lens dose and finger dose is also important for this type of application. The assessment of the effective dose should be further validated. In the clinical validation, we can conclude that the location of the physical dose meter has a great influence on the result. An assessment of effective dose by calculation is of interest and can improve dose assessments including comparison of doses from interventional radiology with other sources of exposure.

The presentation of the output data and how it will be presented to the clinical end-user has been developed by collaboration with the software developer team and the hospital users and further tests on the usability of the complete online system in hospitals are planned as future work.
4.4.3 Consideration for an operational system in the clinic

Based on the challenges described here, in the future, a PODIUM-type solution should be designed to be integrated, discrete, cable-free, battery operated and wireless, with fast performance and it should be easy to mount in an X-ray room in a variety of ways. All equipment must be safe to use in the clinical environment. Along this line new wireless depth-camera-computer available in the market can offer new advantages. Security issues concerning an IT solution introduced into the hospital environment is also a key issue. The ethical issues including concerns of privacy, storing of data have to be considered. – All use of the equipment was performed under research conditions with all the necessary permissions in place. As mentioned above, aspects of user-friendliness including installing a system in the room, and software-related issues such as design and workflow have been commenced and will be tested further.

4.5 Conclusion

A series of experimental set-ups was first used to test the online application in a systematic manner. The operator’s movement tracking was tested on site in an interventional room, by mimicking operator movements without patients involved. The validation experiments were performed using clinical X-ray equipment, where X-ray field size and tilting of the X-ray tube was altered. The operator was simulated using phantoms. In order to simulate the patient, an anthropomorphic phantom was be used. During the experimental set-ups, detailed measurements, from different positions using active and passive dosemeters on the dummies, were performed in order to validate the computed doses. The measurements gave useful information to improve the simulations, source specifications and geometry mapping.

Secondly, a full scale feasibility test in clinical settings during real patient treatment in hospitals was performed. Different procedures were chosen including commonly performed vascular and cardiovascular procedures. The staff dose of different body parts were measured using active and passive dosemeters on relevant positions on the operators. This part of the project was conducted at the St James’s hospital, Dublin, Ireland and at the Skåne University Hospital, Sweden. The clinical environment is necessary in order to gather appropriate information on the performance of an online dosimetry application in the hospital.

The experimental and clinical tests indicated development needs in order to get the full clinical relevance of the online dosimetry application. The possibilities and limitations of the application was explored, taking into account the clinical situation. These first validations in the clinic serve as a valuable input to the improvement of the system. The experience gained from the clinical validation measurements has been used as to develop the recommendations on future needs. The Interventional radiology / cardiology environment is one of the most complex situations for personal dosimetry so it was ambitious yet highly worthwhile to try the proof-of-concept PODIUM approach in this field.
WP5. Assessment and validation of the online dosimetry application in mixed neutron-gamma workplace fields

I. Introduction

Workplace radiation fields in the nuclear industry often contain significant components of dose from photons and neutrons. These are also workplaces where workers can receive relatively large doses of radiation and they pose significant issues for personal dosemeters. Consequently, they are an area where online dosimetry has a lot of appeal, so they were included in the PODIUM project. Whilst the issues with achieving viable online dosimetry in mixed neutron/gamma fields are mainly the same as those involved in the photon fields, there are some distinct differences which make the problem more complex: the need to transport more types of particle; the greater memory requirements for neutron calculations; the greater computation times for neutron calculations; the radiation weighting factors, which cannot be applied in real time Monte Carlo.

II. Selection and specification of the mixed neutron/gamma fields to be used in PODIUM

There are specific difficulties associated with accessing most workplace neutron fields. The primary problems relate to the likely levels of security that will cause difficulty in gaining access for staff that do not have security clearance. Even with security clearance, the level of supervision by staff from the site is likely to restrict the number of people from PODIUM able to enter the workplace and the amount of time that can be spent on a research project. These problems derive from the neutrons typically being generated by highly enriched fuel, spent fuel or weapons-grade materials. If granted access to a nuclear site, there would be restrictions on the equipment that can be taken in, which will apply most strictly to any items able to take images of the facility. For the PODIUM contract, the need to use video images to identify staff would pose specific problems with access. For the commissioning stage, easy access to the field was a priority, so it was always planned that the first stage would be performed in a simulated workplace field at PHE.

II.1. Scoping exercise at PHE

An $^{241}$Am-Be calibration source (UK Secondary Standard) is moderated using either water shields. These shields only partially obscure the neutron source, so that there are significant dose rate gradients in the room. A full MCNP model of the facility itself already existed, and the fluence-energy distribution of the field has been characterized previously. The modelling was now extended to the new shielding configuration prior to the measurements. The field is a mix of fast neutrons from the partially moderated source, and lower energy neutrons from scatter with the shield and calibration room.

Current radiation protection controls do not permit people to be inside the PHE facility with the source exposed. This is not a problem for this test, however: the dose rate map was built-up in advance, so when people moved around within the room, they could be imaged, and their dose rate determined, without them receiving an unwarranted radiation dose.

II.2. Real Workplace

Many options for real workplaces were considered and the contact made with the sites. This was a lengthy and complex process, given the unique nature of the workplaces of interest, and the various security, health & safety considerations and permissions would need to be agreed in advance between the PODIUM consortium and the potential organizations. Contact was made with the management of sites of the types listed in Table 5.1 where the strengths and weaknesses associated with each option are summarized. The suitability of the field is the main driver for PODIUM but access to the site is more complicated for the more interesting fields. Based on the realistic nature of the fields and the relative ease of access, the Research Centre was selected as the best option.
Table 5.1. Summary of workplace neutron fields considered

<table>
<thead>
<tr>
<th>Workplace</th>
<th>Field(s)</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Centre</td>
<td>Transport container with spent MOX fuel</td>
<td>Realistic field; workers get significant doses; relatively easy access</td>
<td>Uncertainties in material compositions make Monte Carlo simulation difficult</td>
</tr>
<tr>
<td>Fuel enrichment facility</td>
<td>$\text{UF}_6$ storage facility</td>
<td>Quite high dose rates; workers get neutron doses; site interested in dosimetry</td>
<td>Site access may not be easy</td>
</tr>
<tr>
<td>Weapons facility</td>
<td>Assembly of block sources in an unused building; VIPER research reactor</td>
<td>Good collaborative links with the lead scientist; fields representative of those to which workers are exposed; the site was interested in taking part</td>
<td>Neither field is “real”; first field would be only marginally more realistic than the calibration field at PHE; the VIPER reactor would be entirely simulated; access to the site may be very difficult</td>
</tr>
<tr>
<td>Pressurized water reactor</td>
<td>Fuel rods whilst being removed from pond storage</td>
<td>Representative of nuclear workplaces; good contacts with the scientists responsible; the site indicated its interest</td>
<td>Moving source may need to be simulated; access may be problematic; fields may not be available on a timescale that fits PODIUM</td>
</tr>
<tr>
<td>Research proton accelerator</td>
<td>Proton beam – stray radiation fields</td>
<td>Good links with scientists who are very interested in the dosimetry; low security restrictions; interesting geometries; the site indicated its interest</td>
<td>High energy fields; not really representative of typical workplaces; Monte Carlo more complex and uncertain</td>
</tr>
<tr>
<td>Fusion research</td>
<td>Fusion tokomak</td>
<td>Scientific establishment with real interest in the fields; relatively easy access; the site indicated its interested</td>
<td>Only able to operate in very short pulses; would need to assume steady state operation and track staff through a real geometry with simulated dose rates; relatively high energy neutrons</td>
</tr>
<tr>
<td>Proton therapy facility</td>
<td>Proton therapy facility with stray neutron fields</td>
<td>Facility with a real need to understand its fields; easy access</td>
<td>High energy fields; more complex Monte Carlo; not representative of most current workplaces</td>
</tr>
<tr>
<td>Nuclear fuel reprocessing facility</td>
<td>Spent fuel flask; reprocessing facility; Pu storage</td>
<td>Realistic fields where workers get doses; established contact with links to the EVIDOS project</td>
<td>Security issues may be too great</td>
</tr>
</tbody>
</table>

III. Radiation Mapping

The need for a two-step process for online dosimetry is driven by the inability of the current Monte Carlo codes to calculated effective dose in anthropomorphic phantoms in a distributed energy neutron field. The method adopted by the PODIUM system for neutron fields is to determine in advance a set of dose rate maps appropriate for the workplace, and apply those in real-time given the tracked motion of the individual. Essentially, this requires the production of appropriate dose rate conversion coefficients that are dependent on the location and orientation of the individual.

The approach adopted is to map the dose rate on a horizontal grid located above the floor at the fixed height or heights. The mapping approach is to generate conversion coefficient data, as well as dose rate magnitudes,
as a function of location within the calibration room. The modelling and measurements in this feasibility study have used a regular grid of points extending over the whole workplace. With the grid defined, conversion coefficient and dose rate magnitude data have been determined for each point on it. The position of the centre of the individual tracked in real time, and the direction in which they are facing, will be ‘snapped’ to the closest position that is defined on the adopted grid. The data rate at that point on the field map will then be used to derive the dose to the individual for the duration for which they can be considered at that location. As the individual moves, his/her position is tracked: eventually it will become closer to one of the other points on the defined grid, which would lead to the selection of a different set of appropriate values from the field map. The process may continue indefinitely.

IV. PHE Simulated Workplace Field

IV.1. Field description

The feasibility of online dosimetry was investigated within the neutron calibration laboratory (Figure 1.11) at PHE’s Centre for Radiation, Chemical and Environmental Hazards (CRCE) in Chilton, UK: the room is concrete walled with dimensions of 8.1 m x 5.2 m x 2.7 m height. At this site, the low-scatter environment routinely used to perform Secondary Standards certified exposures to an $^{241}$Am-Be source incorporates a neutron shield/absorber Premadex® (1), covered by wooden panelling, to produce a relatively low scatter radiation environment (Francis 1992). The standard irradiation facility (Figure 1.12a) was modified by the inclusion of water tanks to produce a location and direction dependent field (Figure 1.12b) that has been shown to be similar in energy distribution to the types of workplace field that can exist at a nuclear power station (Figure 5.1) (3).

![Figure 5.1. Neutron spectra for the reference point behind the water moderator as simulated in MCNP compared to fields measured in the EVIDOS project (3)](image)

IV.2. Comparison of the Monte Carlo fields with spectrometry

A fundamental part of the field verification is the use of neutron spectrometry to experimentally determine the spectrum. Because no Bonner spheres were available to make the measurements at PHE, measurements were made in the PHE simulated workplace field using the Raylab DIAMON neutron spectrometer. This uses a parameterized approach to determine the spectrum, which is not as reliable as Bonner spheres.
The results for the reference moderated position (0,0) and a semi-moderated position (2,0) (Figure 5.2) show that the DIAMON results are broadly in agreement with the MCNP calculated spectra. Although the methodology behind the DIAMON output is not fully disclosed it is pleasing to see that as an independent assessment it appears to yield similar results to the MCNP method at (0,0). The most obvious difference in the results is for position (2,0) where the DIAMON shows the fast neutron peak shifted slightly to a lower energy. It should be noted that for this position the exact positioning of the DIAMON instrument at position (2,0) strongly influenced the dose rate and also the spectrum. This was confirmed by moving the instrument laterally from the nominal grid position a small increment and repeating the measurement. The reason is part of the instrument has a direct line of sight to the source and other parts are shielded by the water phantoms and moving laterally exposes more or less of the detector to the source. The MCNP spectrum reflects the known energy distribution of a $^{241}\text{Am-Be}$ spectrum, so it is evident that the MCNP is more accurate for this location.

![Figure 5.2. Comparison between MCNP spectra and those from the DIAMON instrument](image)

**IV.3. Validation of the Monte Carlo using neutron survey instruments**

The easiest validation of the Monte Carlo is provided by using neutron survey instruments to determine the ambient dose equivalent, $H^\text{*(10)}$, at each reference point. Such instruments have reasonably strong energy dependence of response, but that is well known in most cases and corrections can be made for it.

The $H^\text{*(10)}$ rate was determined at each location of the grid. There are several motivations for this:

- It allows the model to be checked against confirmatory measurements that can be made in the field using readily available instrumentation, such as hand-held survey instruments
- It supports the use of installed monitors in facilities, which will be important for dose normalization and ongoing renormalization, as discussed in the next section
- Permits the implications of radiation surveys made using survey instruments to be compared with online estimation of effective dose: do survey instruments provide significant over or under estimates of effective dose?

The ambient dose equivalent map has been modelled by defining spheres of air of radius $r$ at each position on the grid, where $r$ is small compared to its distance from any source ($r \approx 10$ cm for a 1 m $\times$ 1 m grid). The contribution to $H^\text{*(10)}$ from photons at each location was obtained by determining the fluence-energy
distribution through the sphere and convolving that with the energy dependent fluence-to-$H^*(10)$ conversion coefficients provided in ICRU Publication 57 (4) / ICRP Publication 74 (5), with lin-log interpolation applied at intermediate energies according to the scheme recommended by ICRU; in MCNP, for example, this is readily achieved using a binned $f4:p$ tally in conjunction with $de4$ and $df4$ tally multipliers, where the binning structure is chosen to match the energy grid upon which the conversion coefficient data are tabulated. The contribution to $H^*(10)$ from neutrons at each location may be obtained similarly, but using an $f4:n$ tally, different appropriate $de4$ and $df4$ tally multipliers with different bin structures, and log-log interpolation. Summing the contributions from photons and neutrons provides the total ambient dose equivalent per source neutron; multiplying the result by the known neutron emission rate of the source leads to an estimate of the absolute value for ambient dose equivalent rate at each location.

Initially, the source and grid were set up without the water tanks, walls, ceiling or floor to check the source definition and method. This produced a field with $H^*(10)/\Phi$ conversion coefficients that were statistically consistent with the 391 pSv cm$^2$ given in ISO 8259-1 (ISO 2001). The room structure was then replicated along with the water moderators. This final $H^*(10)$ map (Figure 5.3) shows a strong dependence of the dose rate on the location, with the water tanks significantly perturbing the field. There is symmetry in the data because the room is essentially symmetric, so only results on one side of the room and the central line were simulated. The results are hence mirrored.

![Figure 5.3. $H^*(10)$ dose rate map at a height of 1.25 m. Quoted uncertainties are one standard deviation on the MCNP result; statistical uncertainties only.](image)

The data are also presented as fluence to $H^*(10)$ conversion coefficients (Figure 5.4), which show the “hardness” of the field. As anticipated, the water shield moderates the neutrons, giving a lower mean energy and a consequential lower $H^*(10)/\Phi$ conversion coefficient. Also, as expected, it was observed that proximity to the walls increased the scatter as a fraction of the total field, because the direct source neutrons are reduced by the inverse square law, but the room scatter should be relatively constant through the room.
Figure 5.4. $H^*(10)/\Phi$ conversion coefficient map at a height of 1.25 m. Quoted uncertainties are one standard deviation on the MCNP result; statistical uncertainties only

Validation of the modelling using the $H^*(10)$ map has been obtained using a set of survey instruments, three for neutrons and one for photons: the Guided Neutron Unit (GNU) (6); Tracerco T405 (7); Ludlum Model 23-63/Prescila (neutron and gamma) (8), Tracerco T406 for photons. Measurements were made with each of these at all points on the grid, though there were sensitivity issues with the Prescila so no complete dataset will be presented. The $H^*(10)$ results for the GNU and Tracerco are presented as a ratio (Figure 5.5). There is relatively good agreement between the neutron $H^*(10)$ measured dose rates, though the scatter (Figure 5.5) shows that the Tracerco reads generally lower in these fields, with each instrument being used with its standard calibration. The scatter is quite large, with discrepancies as large as 15%. These are two relatively good neutron survey instruments, and this test is from hard to moderated fields, so the data provide an indication on the state of the art for neutron surveys.

Figure 5.5. Ratio of the readings of the T405 to those from the GNU

The neutron ambient dose equivalent rate results show generally good agreement with the MCNP results (Figure 5.6), most values lying within ±20%. When the reading is corrected for the known response in that spectrum, the agreement is improved, but the remaining differences could be caused by the direction...
dependence of response of the instrument, which is not corrected for. Neutron survey instrument results are not completely reliable (3; 9), but this result merits further investigation.

![Graph showing ratio of MCNP calculated H*(10) neutron rate to the measured H*(10) rate. The measured data are the average for the GNU and Tracerco T405 results.]

**Figure 5.6.** Ratio of the MCNP calculated $H^*(10)$ neutron rate to the measured $H^*(10)$ rate. The measured data are the average for the GNU and Tracerco T405 results.

**IV.4. Evaluation of personal dosimetry**

Personal dosemeters are too imprecise to be used to test the accuracy of the Monte Carlo model. They are used to assess the state of the art in terms of current personal dosimetry; for comparison with online methods.

To compare the readings of personal dosemeters with the personal dose equivalent received requires knowledge of the personal dose equivalent at specific locations. This is not trivial to calculate in Monte Carlo, but in this instance the average kerma factors and quality factor method (10) has been applied in a 30 cm x 30 cm x 15 cm slab of ICRU 4-element tissue (11). In the measurements, the slab is replaced by the ISO water-filled slab of the same dimensions (12).

To obtain the direction dependence of $H_p(10)$ it is necessary to rotate the slab of ICRU tissue to the desired angle, which requires a separate Monte Carlo run for each direction of interest. However, because of the symmetry of the phantom it is possible to score $H_p(10)$ under both of the large faces of the phantom, and hence obtain two values in the same Monte Carlo run, albeit for opposite directions and positions separated by 13 cm. The angle convention used for effective dose (see below) is also applied to personal dose equivalent.

Because the personal dosemeters used are not very sensitive, it has only proved possible to make measurements at a subset of the points on the grid, so initially the personal dose equivalent determination (both measured and calculated) has only taken place for a small subset of the points used for ambient dose equivalent and effective dose. It is evident that online dosimetry will permit the estimates of personal dose equivalent which are less influenced by a reporting threshold than measurements with physical dosemeters are.

Given that the PODIUM project seeks to improve on current methods, for mixed neutron-photon fields, where estimates of effective dose have specific problems, it may prove preferable to provide online estimates of personal dose equivalent. In particular, because personal dose equivalent uses the quality factor rather than the radiation weighting factor, it is much more feasible that direct estimates of personal dose equivalent could be made using real time Monte Carlo.
Because the PODIUM project outcomes will ultimately be compared with personal dosimetry, the exposure of personal dosemeters in the workplace fields is an important part of the project. The inclusion of workplaces with neutron fields in PODIUM is connected to the acknowledged poor performance of neutron personal dosemeters in practice (3;13;14). It follows that the exposures of personal dosemeters is not a part of the validation of the fields, but instead they are to be used to compare with the accuracy of effective dose evaluations.

Four passive personal dosemeter types were used in these measurements as well as one active design (Figure 5.7):

- Landauer Neutrak® chemical etched track dosemeter (CETD)
- PHE electrochemically etch track dosemeter (ECETD)
- Thermoluminescent albedo dosemeter (TLAD)
- Chemically etched track dosemeter with thermal TL element (CETDTL)
- Thermo-Fisher EPD-N2 active personal dosemeter (APD)

![Figure 5.7](image)

Figure 5.7. The PHE field, showing the three measurement locations with dosemeters mounted on ISO water filled phantoms, source tube (yellow), and two water containers (white).

Analysis of the results has used the response of each dosemeter type, that is, the ratio of the $H_p(10)$ measured by the dosemeter to the MCNP calculated $H_p(10)$ (Figure 5.8). The phantoms are oriented with the front face facing toward the source. With dosemeters mounted on the front and rear of the phantoms this mimics the situation of a person either facing the source or facing away from the source, although there will obviously also be a scattered neutron contribution at the three positions. The results shown are the average of two separate measurements made during December 2018 and Easter 2019. Where possible multiple dosemeters of each type were used on the phantom face to improve overall statistics, however, this introduces extra variation in the results where the field across the phantom face is not uniform. The responses determined have only used the MCNP calculated value for the centre of the phantom face, so this variation is not corrected for in the results.

Measurements and calculations of $H_p(10)$ have been performed at three locations, with the phantom centred at coordinates (0,0), (2,0) and (2,-2). For each location, results were obtained for both the front and back of the phantom, assumed to represent two opposite orientations of an individual within the field. The MCNP simulations were used to calculate both the neutron and photon components of the personal dose equivalent. The Thermo Fisher EPD-N2 was also able to measure these two components separately, for subsequent comparison against the Monte Carlo data, but the PADC is intended to be insensitive to photons so only determined the neutron component. For the PADC, a routine calibration response of $0.84 \times R(^{241}\text{Am-Be})$ was applied.

In general, the modelled data agree with the PADC measurements to within a few 10s of percent, which is encouraging, but less well with the EPD-N2 results. This latter observation is perhaps as anticipated, because the EPD is expected to exhibit a poorer response in the PHE set-up, and demonstrates one advantage of the PODIUM approach relative to the use of dosemeters. However, the lack of agreement for photons could also indicate a limitation in the model for this component of the field, especially as additional $H_p(10)$ measurements for photons made with the PHE $\beta/\gamma$ thermoluminescence dosemeter (TLD), which incorporates Harshaw TLD700H $^7\text{LiF:Mg,Cu,P}$ and is routinely issued to provide accurate estimates of photon personal dose equivalent, showed similar results to the EPD-N2™.

Personal dosemeter measurements have shown that there is significant variation for the dosemeters tested. This is anticipated, because it is well known that neutron personal dosemeters have significant variations in their response (13). The generally good agreement, within a few tens of percent, between the readings for the PHE PADC dosemeter and the Monte Carlo modelling is encouraging, and other systems have produced acceptable results but with more variable responses, being slightly low on the back faces of the phantoms. Some of this variation will be inherent from the way in which the dosemeter is calibrated and how applicable that method is to the neutron field energy and angle distribution present at each position, with some systems normally requiring a priori information on the type of field.
**IV.5 Comparison with effective dose**

For the reasons discussed elsewhere (WP1) it is not possible currently to determine the neutron effective dose directly, for instance by introducing a voxel phantom into the model, with the difficulty of applying the correct radiation weighting factors in a distributed energy field providing the greatest barrier. Instead, a ‘spectral’ method of determining effective dose indirectly has been developed within PODIUM. The procedure involves calculating the energy and angle distributions of the neutron and photon fields, as well as their magnitudes, at each location on a discrete grid; these data can then be convolved with energy and angle dependent fluence-to-effective dose conversion coefficients, with the two components then summed to provide a map of the total effective dose rate, subsequent to appropriate normalization based on the source activity. The effective dose to an individual is subsequently calculated in real time within PODIUM by tracking their motion around this dose rate map.

The method used to generate the effective dose rate map is described in WP1. For the PHE field, mapped on a 1 m × 1 m grid at a height of 1.25 m from the ground, which is the height of the 241Am-Be source, 8 orientations of the individual were considered, equally distributed in φ=45° increments. Within the Monte Carlo model, 8 horizontal cones of half-angle θ=22.5° were used, along with two vertical cones of half-angle 67.5°. For the fluence tallies in the horizontal cones, an areal correction factor of $C_A = 1.257 \times$ was applied, which ensured that the full $4\pi$ solid angle was accounted for at each location.

For the purposes of discussion, the reference direction is assigned to the positive y-axis, with angles then defined relative to this in a clockwise manner. Thus, for an individual standing at the origin (i.e. the reference position, behind the water tanks), an orientation of $180°$ would correspond to them facing the source, whilst $315°$ would imply that they were facing roughly in the direction of the laboratory door, for example.

The effective dose rate map has been provided for only half of the room. The laboratory is symmetric, so the mirror image of this map could possibly be used to provide the full dose rate map for the facility, as was done for the $H^*(10)$ map. However, this would only be an approximation: whilst $H^*(10)$ is an isotropic dose quantity, effective dose is not because the body is not symmetric, so for example LLAT exposures on the left side of the room differ slightly from RLAT exposures on the right side of the room. Nevertheless, this is not expected to be a problem within the current proof-of-concept of the PODIUM approach.

Generation of the neutron dose rate map was highly labour intensive. Each location required the analysis of 66 separate tallies (= 8 effective dose components × 8 orientations, + 2 vertical), requiring 1518 results in total for the grid (= 23 locations × 66 tallies). In principle, this effort should then be doubled to provide the concurrent photon effective dose rate map, but this was not performed for the PHE facility, for which the photon component was shown earlier to be small. Extraction of the data from the MCNP output files and their processing in Excel was performed manually, but it may be presumed that in a future approach to online dosimetry much of this analysis could be automated using bespoke data grab and manipulation software or macros, so the current complexity of the task is not necessarily a fundamental limitation of the PODIUM approach.

The neutron effective dose rate map generated for the PHE workplace field facility is shown in Figure 5.9, for an individual facing in the eight different orientations considered. The one standard deviation uncertainties relate just to the statistical fluctuations within the Monte Carlo calculation.
<table>
<thead>
<tr>
<th>Angles</th>
<th>Effective Dose Rate:</th>
<th>uSv/hr</th>
<th>1sd</th>
<th>uSv/hr</th>
<th>1sd</th>
<th>uSv/hr</th>
<th>1sd</th>
<th>uSv/hr</th>
<th>1sd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(0,Y)</td>
<td>(100,Y)</td>
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<td>135 Degs</td>
<td>Effective Dose Rate:</td>
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<td>180 Degs</td>
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Figure 5.9. Effective dose rate map in the PHE facility, for individuals facing in 8 different directions.

It is almost impossible to measure effective dose physically: doing so would require filling an anthropomorphic phantom (e.g. RANDO phantom) with dosemeters to estimate organ doses, before combining their results to generate effective dose, for which the previously identified difficulties in applying the correct $w_R$ would again manifest. Accordingly, the results in Figure 5.9 have not been verified directly within PODIUM. Nevertheless, previous good agreement between modelled and measured $H^*(10)$ dose rates provide confidence in the veracity of the model of the underlying room geometry. Moreover, analyses and comparisons between the effective dose rate maps and the ambient dose equivalent rate map demonstrate the anticipated trends and patterns, both in terms of their individual self-consistencies, and in their relative similarities and dissimilarities given the similarities and dissimilarities in the two differently defined dose quantities. For example, at locations close to the source and away from the moderating water tanks, the measured $H^*(10)$ rate is commensurate with the effective dose rate for an individual orientated towards the source (i.e. a predominantly AP-like exposure), but much higher when orientated away from it. In fact, in the most uni-directional cases, $E$ is seen to be a little greater than $H^*(10)$, likely due to the anticipated slight overweighting by the correction factor $C_A$ as well as the greater value of the fluence to effective dose conversion coefficient at higher energies (15). On the other hand, at locations in the room where the field might reasonably be expected to be relatively isotropic, the effective dose rates are seen to be relatively independent of the individual’s orientation, compared to those locations where the field is expected to be more directional.
The last of the above points is illustrated in Figure 5.10, in which the effective dose rates for each of the eight orientations are shown on radial plots at five locations close to and around the source; the coordinates of these locations are shown on the key. Both log and linear axes are used for the plots, with the datasets themselves identical in both cases: the log plot better clarifies the relative isotropy behind the water tanks (e.g. at (0,0)), whilst the linear plot shows the anisotropy away from the water tanks (e.g. at (0,-200)). Nevertheless, the relative smoothness of the data in Figure 5.10 also suggests that the 45° angle binning used in the Monte Carlo modelling is probably adequate for the purposes of real-time dosimetry and that further interpolation is not necessary, noting also that many workplace fields are likely to be more isotropic than that considered here.

**Figure 5.10.** Effective dose rates (μSv h⁻¹) for individuals facing in 8 different orientations (45° increments) at five locations around the source, using log (left) and linear (right) axes.

**IV.6. People tracking**

With the effective dose rate map determined it was possible to combine it with the Kinect camera (Figure 5.11) and accompanying software so that individuals could be tracked around the facility and their doses estimated. However, due to local rules on safety constraints, this exercise could only be mock: the ²⁴¹Am-Be source had to be kept shielded whilst individuals were inside the facility, so the subsequent output ‘doses’ relate just to what would have been received had it been a real exposure. Nevertheless, the exercise provided a valuable overall test of the integrated PODIUM approach.

**Figure 5.11.** Kinect camera within the PHE facility.

At least two cameras would be installed if the PODIUM approach were being used to provide real-time dosimetry in a room the size of the PHE facility, with three more likely optimal to provide full coverage: one
in each corner, excluding by the door (see WP1). However, only one camera was available for the test, leading to a limited field of view. This was not a problem for the intended proof-of-concept, however, if the individual being tracked stayed within the active area. The camera was placed on a tripod in one corner of the room at a height of ~2 m (Figure 5.11), providing good coverage of the central region of the facility (Figure 5.12, upper left: the non-trackable region is highlighted yellow).

Figure 5.12. Kinect registration within the PHE facility. The non-trackable region is highlighted yellow.

Configuration of the Kinect followed the procedure described elsewhere (WP1). Positional calibration of the Kinect relative to the laboratory frame-of-reference was achieved using the SCK-CEN Kinect Registration software (Figure 5.12), with the tilt and yaw angles of the camera relative to the axes of the room’s coordinate system measured using ancillary electronic sensors. The coordinate parameters outputted by the Registration programme were checked against confirmatory distance measurements made in the laboratory, before being included in the dose rate map input file ready for subsequent use. This dose rate map input file was essentially just a plain text version of Figure 5.9, appended with coordinate transformation instructions and data and prepared in a programme-readable form (Figure 5.13) that could subsequently be taken as input by the dose conversion executable.

Figure 5.13. Dose rate map input file.
Tracking within the laboratory was achieved using the BodyBasics-WPF.exe programme, using a motion capture frequency of 1 Hz and a video rate of 1 frame-per-second, though the latter served only as a record and is not required for the dosimetry algorithm. Only the upper body was tracked by the programme, which is sufficient for the present method of neutron dosimetry because only the location of the centre of the individual to the nearest 1 m is required, along with their orientation.

The motion of individuals was tracked (Figure 5.14) for durations of ~100s, as they rotated and moved around within the facility. The obvious endeavour was for the individual to move between locations of both high and low dose rate, and face in different orientations at locations of both strong and weak directional dependence, to provide the fullest possible test of the PODIUM approach. Data on the individual’s tracked movement was stored in a comma separated value (.CSV) file created by the BodyBasics-WPF programme, which provided a second-by-second log of their position and orientation.

The dosimetry was performed using the neutron_dose_calculation_module.exe application. The application takes as inputs the text file of the dose rate map and the .CSV tracking file and returns an output that details both instantaneous and time-integrated doses. It achieves this by taking the position and angle data at each capture (in this case, every second), and rounding them to the nearest 1 m × 1 m grid location and 45° increment of orientation; the orientation of the individual is determined by considering the angle subtended between the shoulder line and the coordinate axes. The application then uses the map file to look-up the dose rate corresponding to that location and orientation, which it can then apply. This process is repeated for every capture logged within the .CSV tracking file, to provide a record of the dose received during each second of the individual’s motion.

As an example, Figure 5.15 (left) shows the captured (x,y) motion (blue points) of an individual within the PHE laboratory, relative to the usual axes and origin, along with the locations on the 1 m × 1 m grid that these positions would have been 'snapped to' (orange points). Figure 5.15 (right) shows the corresponding effective dose rate to with the individual was exposed at each second of their motion around the facility. The neutron_dose_calculation_module.exe application also provided an estimate of the total dose, essentially by
integrating the data in Figure 5.15 (right) over the entire duration of the tracking. In this current example, a total effective dose of 1.25 μSv was found.

It is not possible to verify the above result of 1.25 μSv experimentally because of the complications in physically measuring effective doses, as well as logistical difficulties in moving phantoms around the PHE facility with the source unshielded and the long exposure times that would be required due to the fairly low dose rates emitted by the 241Am-Be. However, an heuristic analysis of the effective dose rate maps (Figure 5.9), such as by taking a rough average of the datasets corresponding to the positions shown in Figure 5.15 (left), suggests that doses of the order of ~1 μSv might indeed be anticipated from an exposure lasting around one and half minutes at these locations.

![Figure 5.15. Tracked motion of individual (left) and corresponding effective dose rate applicable at each 1s time interval (right).](image)

A further indirect check was also performed by modifying the dose rate map input file, replacing the effective dose data with the analogous data for ambient dose equivalent (Figure 5.3). Rerunning the neutron_dose_calculation_module.exe application using the same tracking file then gave a total H*(10) dose of 1.4 μSv. This result is commensurate with, though a bit larger than, the concurrent total effective dose, which is broadly as expected for the two different dose quantities.

It is noteworthy that the 1.25 μSv effective dose recorded by the PODIUM system, for which dose rates as low as 0.5 nSv h⁻¹ have been accounted for and applied, is much lower than anything that could be reliably and accurately measured by physical dosemeters in such a field. This capability demonstrates a significant potential advantage of the PODIUM approach over conventional dosimetry, in addition to its advantage of estimating effective doses rather than just personal dose equivalent.

V. SCK•CEN Workplace Field

V.1 Introduction

The second measurement campaign was in a more realistic neutron workplace field, where not all details of the neutron field were known, and where temperature and environmental conditions can change. Such a realistic neutron field was found at SCK•CEN.

For this SCK•CEN field one MOX fuel transport container was placed at a specific location, so that measurements could be made around this container without disturbing other activities in this hall. This container was filled with MOX fuel rods, so that sufficient neutron dose rates could be measured. Around
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this container, SCK•CEN and PHE did measurements with as many neutron dosemeters and spectrometers as could be obtained, and an IPS (indoor positioning system from WP1) was also installed at this location. The measurements hence took place from June to September 2019.

V.2. Monte Carlo modelling

The field is representative of infrequent high neutron dose rate activities carried out in the facility. It relates to the storage of high burn-up mixed oxide (MOX) fuel rods inside a thick lead shield (Figure 5.16). The purpose of the lead is to shield the intense photon field from the fission fragments in the fuel, which is likely to be dominated by Cs-137 photons, although there will be additional photons from the fuel itself as well as other fission fragments. The lead shield is not expected to cut down the neutron dose rate very significantly because neutrons lose very little energy in elastic scattering events with lead nuclei. Down-scattering in energy should be anticipated, but there should be little thermalization of the field by the lead.

The fuel rods are over 30 years old with a complex history in two different nuclear reactors. They were used in the Belgian Reactor 2 (BR2) until 2014. Consequently, specification of the exact source term is not possible, but a “cooling time” of about 5 years can be assumed for this project. Because nuclear facilities will be one of the key targets for the PODIUM system, it is important that this issue can be addressed in this test.

The fuel flask was in a quiet part of the facility (Figure 5.16), resting on a concrete floor. There was a lead shield in the floor, to reduce dose rates from a cell below, and a drop to a lower floor on two sides. The concrete wall is closer on one side and there are metal objects (chains) on the wall that may provide significant scatter. The ceiling is relatively high and the walls on two sides of the room relatively distant. Complex equipment is located beyond each end of the room beyond the ends of the flask, but distance makes it unlikely that this needs to be included in the MCNP model.

Figure 5.16. The fuel flask in the measurement position. The grid locations for the field determination are marked by tape on the floor. This figure shows two ISO slab phantoms with personal dosemeters mounted for determination of the accuracy of personal dosemeters.

The key aspects of the room to simulate are the concrete walls and floor and the lead shield within the floor. It was decided that other small features would be omitted, unless there was strong evidence from the measurements that they should be added to the model. The flask (Figure 5.17) contained four fuel rods,
which were located inside the internal cavity. The precise location of these fuel rods could not be known, without opening the fuel flask to inspect them, which would incur significant photon and neutron doses. It was assumed that they are in the centre of the fuel flask, resting on the bottom of the inner cavity.

The workplace was labelled using an x-y grid (Figure 5.18) with 25 cm spacing, and at 3 different heights (18-55-125 cm). This was used for fine grid measurements using neutron survey instruments and for modelling the field. Subsequent tracking of people will snap the position of the people to the closest point on this grid. Representative reference positions were added to this grid for additional characterization of the field using personal dosemeters and Bonner spheres. These are labelled positions A-G. Most were at 1.25 m height to represent a standing person. Positions C and F are at the same (x,y,z) location, but F is rotated by 45° around the z-axis relative to position C to test personal dosemeter sensitivity to direction: for $H^*(10)$ they are equivalent. A, the highest dose rate location, was chosen to be 55 cm to represent a crouching person working on the flask, and E was chosen to be 18 cm high.

![Figure 5.17. The fuel flask. Left, a photograph of an equivalent fuel flask; right, technical drawings of the design](image)

![Figure 5.18. The x-y grid for designating the field. The positions A-G were selected for additional measurements.](image)

The focus for the measurements and characterization was on the left side of the field as viewed in Figure 5.16. This was because a person passing by the flask would naturally pass on that side owing to the greater space. Reference points were chosen to relate to standing person except for one lower position, which was the worst-case scenario of a worker crouching to take a contamination measurement of swab from the flask.
Inverse square considerations, and the location half way along the flask would make this the highest dose rate that a worker could feasibly experience.

The fuel rods were 30 years old and there was no detailed information available on the precise fuel composition or burn-up. It was anticipated that these would be key factors in determining the neutron spectrum and the emission rate, but the sensitivity of the results to the specification of the source is an important test for this real workplace application. The emission rate is not determinable from the information available, but that is not a significant problem: the simulations were normalized to the ambient monitor measurement at position C. As discussed in WP1, normalization of simulation results to measurements with one or more fixed ambient monitors will be necessary when using the PODIUM approach in neutron workplace fields.

Mixed-oxide fuel is generally a mix of UO\textsubscript{2} and PuO\textsubscript{2}, with the uranium being unenriched. Typically, the plutonium to uranium ratio is about 7:93, though this will change during use because of both the fission that takes place and the neutron capture that introduces higher A isotopes and consequently higher Z elements via beta decay. MOX fuel in a sub-critical state emits neutrons via spontaneous fission and (\alpha,n) reactions. The ratios of these, and the elements responsible, change with the degree of burn-up and the cooling time (16;17;18). Few isotopes have significant (\alpha,n) cross sections because the Coulomb repulsion is too great. This is especially true for high Z elements, but also for isotopes such as \textsuperscript{16}O. Notable exceptions are \textsuperscript{6}Li, \textsuperscript{7}Li, \textsuperscript{9}Be, \textsuperscript{10}B, \textsuperscript{11}B, \textsuperscript{17}O and \textsuperscript{18}O. In the case of MOX fuel, the two oxygen isotopes are crucial, though \textsuperscript{17}O constitutes only 0.038\% of natural oxygen and \textsuperscript{18}O 0.204\%. The cross section for \textsuperscript{18}O peaks at about 0.8 b whereas that for \textsuperscript{17}O reaches about 0.4 b (19), so clearly owing to its 5 fold greater incidence and higher cross section, \textsuperscript{18}O should dominate the (\alpha,n) production of the fuel. However, a confounding factor is the negative Q-value for \textsuperscript{18}O, which will lead to lower energy neutrons than are emitted by \textsuperscript{17}O, which has a positive Q-value (Table 5.3). However, both reactions have very small Q-values when compared to that for \textsuperscript{9}Be, the best characterized emission spectrum.

Neither MCNP6 (20) and MCNPX (21) include (\alpha,n) cross section data, so even though they can transport \alpha-particles, they cannot be used to generate (\alpha,n) spectra. The most obvious spectrum to use for the (\alpha,n) component of the field is \textsuperscript{241}Am-Be (22), but the neutrons from oxygen will inevitably have lower energy because of the lower Q-value. The spectrum is reported to have a peak in the region 2.5-3 MeV and a maximum energy of about 5 MeV (16), which compares with the mean of 4.4 MeV for \textsuperscript{241}Am-Be, for which the maximum neutron energy is over 15 MeV.

Table 5.2. Data for key isotopes for (\alpha,n) reactions

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Maximum cross section</th>
<th>Threshold \alpha-particle energy</th>
<th>Q-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textsuperscript{9}Be</td>
<td>0.8 b</td>
<td>~ 2 MeV</td>
<td>5.70 MeV</td>
</tr>
<tr>
<td>\textsuperscript{17}O</td>
<td>0.4 b</td>
<td>~ 2 MeV</td>
<td>587 keV</td>
</tr>
<tr>
<td>\textsuperscript{18}O</td>
<td>0.8 b</td>
<td>~ 3 MeV</td>
<td>-696 keV</td>
</tr>
</tbody>
</table>

The key factor that changes the ratio of (\alpha,n) to spontaneous fission neutrons is the in-growth of the curium isotopes, \textsuperscript{242}Cm and \textsuperscript{244}Cm (23). These have high spontaneous fission decay rates but are only created in the fuel after multiple neutron captures and \beta-decays. Of the two, \textsuperscript{244}Cm has the longer half-life and hence it dominates once the fuel has spent about a year cooling (Figure 5.3) (17). The (\alpha,n) reactions are also stronger in fuel that has not spent a long time cooling because of short lived \alpha-emitters that have been generated in...
the reactor, so there is a more rapid decline in those reactions than there is in the spontaneous fission: after about 2 years cooling the \((\alpha, n)\) component of the field should be less than 5% of the total neutron emission (16).

Because the fuel is known to be high burn-up, and to have been removed from storage for these experiments, it is initially assumed to have a dominant spontaneous fission neutron yield, though tests using a \(^{241}\)Am-Be energy distribution have also been used to check for sensitivity. This seems reasonable in the absence of a credible \(^{18}\)O\((\alpha, n)\)^{21}Ne spectrum. The results will still need to be normalized to fit experimental data using the reference neutron survey instrument for this project (6) and the results from Bonner spheres.

**Table 5.3.** Relative fractions of spontaneous fission and \((\alpha, n)\) neutrons from MOX fuel versus cooling time (16). The fuel in this work had a cooling time of about 5 years, but these fractions will also be dependent on the burn up of the fuel.

<table>
<thead>
<tr>
<th>Cooling time (y)</th>
<th>Spontaneous fission component</th>
<th>((\alpha, n)) component</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>83.0%</td>
<td>17.0%</td>
</tr>
<tr>
<td>1</td>
<td>90.3%</td>
<td>9.7%</td>
</tr>
<tr>
<td>2</td>
<td>94.9%</td>
<td>5.1%</td>
</tr>
<tr>
<td>3</td>
<td>96.2%</td>
<td>3.8%</td>
</tr>
<tr>
<td>5</td>
<td>96.0%</td>
<td>4.0%</td>
</tr>
<tr>
<td>10</td>
<td>95.6%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

To test for isotopic sensitivity of the spontaneous fission spectrum on the isotopic mix, there are two options available in MCNP6.1: use the simple Maxwell distribution or the detailed emission spectrum for specific isotopes. The latter was preferred on the grounds of greater accuracy. The model for this stage used only a representation of the fuel rod (Figure 5.19). The results (Figure 5.20) show relatively weak sensitivity to element or isotope, though the spectrum for \(^{239}\)Pu differs significantly from the others, being lower in mean energy, though ultimately the impact on the dose rate in the workplace is the sensitivity that is important. However, given that the yield from \(^{239}\)Pu is expected to be orders of magnitude lower than those from curium isotopes (23), so given the similarity between the other energy distributions it is considered that either an average spectrum or the \(^{242}\)Cm spectrum can be used as the emission spectrum.

![Figure 5.19. MCNP setup of the simplified fuel rod (note the horizontal and vertical scales are different)](image)

The fuel flask has been modelled using both the average \(^{241}\)Am-Be (Figure 5.21) and spontaneous fission (Figure 5.22) spectra. These show spectra with very similar energy distributions, which is reassuring in terms of uncertainty and the possibility of applying MCNP in nuclear fuel cycle locations where the source is not
well known. The difference in the magnitude of the fluence for the two different sources is of no concern because normalization to the Bonner spheres or survey instruments is still required. Position A has the highest fluence rate, which is anticipated because of inverse square effects. No data are shown for Position F because that is a simple rotation of Position C, which alters the $H_p(10)$ but not the fluence or $H^*(10)$.

The comparison between the two sources for Position A after normalization (Figure 5.23) shows that the fields are not very different. They have thermal neutron components that are negligible but almost identical in magnitude, very little in the way of intermediate neutrons and fast peaks with a maximum between 1 and 2 MeV. The fast peak for the $^{241}$Am-Be source is a bit broader in energy, but this has very little impact on the fluence weighted average $H^*(10)$ conversion coefficients for the two computations (Table 5.4): the spontaneous fission source produces 3-4% higher values, which is insignificant compared to other experimental uncertainties.

Finally, the geometry of the fuel rods was also made more realistic taking into account the most important components and the actual geometry of the 4 separate fuel rods at the bottom of the container cavity.

**Figure 5.20.** Spontaneous fission spectra from the model of the fuel rod (Figure 5.19).

**Figure 5.21.** Spectra for the reference positions for the field modelled using a $^{241}$Am-Be energy distribution for the source
Figure 5.22. Spectra for the reference positions for the field modelled using a spontaneous fission energy distribution for the source. The difference in the y-axis scale is not important because these data need normalization to survey instrument or spectrometer results.

Figure 5.23. Results for Position A, normalized, for spontaneous fission and $^{241}\text{Am-Be}$ sources

Table 5.4. Monte Carlo calculated fluence averaged conversion coefficient, $H^*(10)/\Phi$ (pSv cm$^2$), for a $^{241}\text{Am-Be}$ source ($\alpha,n$) and a spontaneous fission source, versus location

<table>
<thead>
<tr>
<th>Location</th>
<th>MCNPX, ($\alpha,n$) (pSv cm$^2$)</th>
<th>MCNP6.1, SF (pSv cm$^2$)</th>
<th>Ratio: SF/($\alpha,n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>312</td>
<td>322</td>
<td>1.03</td>
</tr>
<tr>
<td>B</td>
<td>257</td>
<td>266</td>
<td>1.04</td>
</tr>
<tr>
<td>C</td>
<td>287</td>
<td>296</td>
<td>1.03</td>
</tr>
<tr>
<td>D</td>
<td>283</td>
<td>292</td>
<td>1.03</td>
</tr>
<tr>
<td>E</td>
<td>303</td>
<td>313</td>
<td>1.03</td>
</tr>
<tr>
<td>G</td>
<td>242</td>
<td>249</td>
<td>1.03</td>
</tr>
</tbody>
</table>

V.3. Comparison of the Monte Carlo fields with spectrometry

Two different methods of performing the spectrometry experimentally were used: Bonner spheres and a DIAMON detector$^2$ (Figure 5.24). The Bonner spheres require a sequential set of measurements in a location

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(taking about 2 hours in total per location) whereas the DIAMON can make the field determination in a single measurement (taking about 10 minutes per location). Furthermore, the DIAMON also has real-time deconvolution using a parametric description of the neutron fluence energy spectrum. For the Bonner sphere measurements, a set of 8 spheres (3”, 4”, 5”, 6”, 7”, 8”, 10” and 12”) and a Centronic SP9 spherical 3He proportional counter were used. The response functions were simulated using MCNP and validated by measurements with the bare proportional counter in the thermal neutron beam of the SCK•CEN Belgian Reactor 1 (BR1) and with the 8” sphere at the SCK•CEN Laboratory for Nuclear Calibration with 252Cf.

Figure 5.24. Spectrometry measurements: left top and bottom Bonner spheres; right DIAMON

Two different unfolding methods were used with the Bonner sphere data: the programs FRUIT (24) and an algorithm developed by SCK•CEN and PTB in Winbugs (25) were applied. Both methods use the same parametric description of the neutron fluence energy spectrum. However, FRUIT uses a simple random walk approach to find the optimal parameters, while the algorithm in Winbugs uses a Bayesian approach. As the unfolding is a strongly underdetermined mathematical problem one can expect differences between the two methods. There are indeed some evident differences between the Winbugs (Figure 5.25) and FRUIT (Figure 5.25) results. The thermal peaks are very similar for both programs but there is a much stronger intermediate component for Position B in the FRUIT results; Position D produces a much narrower fast peak using FRUIT; Position G has a lower peak energy using FRUIT.

The DIAMON instrument uses a concentric array of detectors within a single polyhedral moderator. It unfolds the spectrum in real time and can hence give a very quick result for the field (Figure 5.25). The main features of these spectra are visually similar to those from the Bonner spheres, though the fast peak is strictly fixed in energy. This probably derives from the parameter based unfolding method which may not be able to vary as many features of the field as is possible in Bonner sphere unfolding.

Currently, the DIAMON calculates the total neutron spectrum and the H*(10) rate, though in real time it can give information on the direction of the neutron field. This capability was evident during measurements when it could detect the contributions from scattering objects. Development of this aspect of the response could lead to direct estimation of effective dose, which would enable dose rate mapping of a workplace without the need for either Bonner spheres or Monte Carlo calculations. Further development and validation is, however, required.
The measured and calculated spectra are compared in Figure 5.25. The agreement is acceptable. In general, the magnitude of the thermal and fast peaks and the position of the fast peaks are in good agreement. It only seems that the fast peak is typically narrower and slightly shifted towards higher energies in the simulations. This can be due to uncertainty in the energy spectrum of the neutrons emitted by the source. For position G it also seems that the thermal peak is significantly higher in the simulations. This can be caused by the fact that this position is close to the wall and thus strongly affected by scattered neutrons from the wall. The simulation of the scattered radiation is strongly influenced by the composition of the concrete of the wall and especially by the hydrogen content, which is not well known. However, the contribution of the thermal peak to the staff dose is very small.

As may be anticipated from the comparison of the spectra (Figure 5.25; Table 5.5), the lower energy of the fast neutron peak from the experimental spectrometry gives lower fluence weighted conversion coefficients for the fields in the reference locations. The differences range from +7% for the most significant location, A, to +37% for B. The results for B are almost certainly caused by the model having insufficient shielding at the end, where the technical drawings of the flask are least clear and the geometry most complex.

Figure 5.25. Spectra for the six distinct locations (F ≡ C) unfolded from the Bonner sphere readings using FRUIT and Winbugs, measured with DIAMON and simulated with MCNP
Table 5.5. Experimentally determined fluence averaged conversion coefficients, $H^*(10)/\Phi$ (pSv cm$^2$) for the six locations determined using the Bonner spheres with FRUIT or WinBugs, and the DIAMON. The results are compared to the mean Monte Carlo (MC) result.

<table>
<thead>
<tr>
<th>Location</th>
<th>FRUIT (pSv cm$^2$)</th>
<th>WinBugs (pSv cm$^2$)</th>
<th>DIAMON (pSv cm$^2$)</th>
<th>Mean MC (pSv cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>277</td>
<td>269</td>
<td>243</td>
<td>288</td>
</tr>
<tr>
<td>B</td>
<td>164</td>
<td>169</td>
<td>178</td>
<td>233</td>
</tr>
<tr>
<td>C</td>
<td>206</td>
<td>195</td>
<td>209</td>
<td>262</td>
</tr>
<tr>
<td>D</td>
<td>236</td>
<td>196</td>
<td>191</td>
<td>258</td>
</tr>
<tr>
<td>E</td>
<td>223</td>
<td>220</td>
<td>236</td>
<td>279</td>
</tr>
<tr>
<td>G</td>
<td>184</td>
<td>186</td>
<td>199</td>
<td>219</td>
</tr>
</tbody>
</table>

V.4. Validation of the Monte Carlo using survey instruments
A total of five different types of neutron survey instrument were used for these measurements as part of the field verification process (Figure 5.26):

- GNU, a spherical moderator-based design that is very well characterized in terms of response versus energy and direction
- LB6411 a spherical moderator type
- Tracerco T405 - smaller spherical moderator
- WENDI – a moderator type with a cylindrical moderator
- PRESCILA – scintillator design

It is important to recognize that neutrons survey instruments are known to give results with systematic biases, but those biases are predictable when the energy distribution is known (9). The instruments are all calibrated in terms of $H^*(10)$ and have been used to determine the dose rate at the six reference positions ($H^*(10)$ for CeF): the results confirm that the dose rate at A is significantly higher than that at any of the other positions (Figure 5.27).

Figure 5.26. Survey instrument measurements, left to right: GNU at 18 cm; PRESCILA at 125 cm; GNU at 125 cm; Tracerco T405 at 18 cm.
At this stage any normalization of the dose rate data is somewhat arbitrary. An initial comparison uses the average Bonner sphere result for the normalization (Figure 5.28) on the basis that these may be expected to provide the most reliable result, given that they are intrinsically corrected for the spectrum. The striking feature of these data is the low response of the PRESCILA in all locations. Inspection of the response of this instrument (26) is the very significant under-response that it has in the energy range 500-800 keV. This is hence a strong indicator that the fast neutron peak of the field is in that energy range.

The DIAMON detector and the Bonner spheres differ from the survey instruments because they determine the spectrum and then use that to determine $H^\ast (10)$. Conversely, the survey instruments attempt to evaluate the $H^\ast (10)$ in a manner that does not depend strongly on the spectrum. In this case, there is generally very good agreement between the DIAMON and the Bonner spheres: the poorest agreement is for position D, but there the DIAMON agrees closely with the Winbugs result, which differs by over 20% from the FRUIT result. The Bonner sphere results differ because FRUIT generates a much narrower fast neutron peak than Winbugs (Figure 5.25).
More puzzling is the under-response of the LB6411 in positions A and D. That instrument under-responds to thermal neutrons and around 100 keV (27), but none of the solution spectra have strong components of dose in either energy range. Similarly, the over-response of the T405 for position B should require significant epithermal contribution, but none of the spectrum determinations indicate that. The DIAMON response is highest for G, where the WENDI, GNU and T405 also over-respond. This is the position closest to the wall, so there may be more scatter from the wall than is being accounted for. Generally, the survey instruments offer strong support for the Bonner sphere results. The agreement is mostly within 10%, which is a good result in neutron dosimetry.

Figures 5.27 and 5.28 also show the simulation results with MCNP in comparison with the measurements. As the simulation results are normalized to the Bonner sphere measurements for position C, by definition, good agreement is expected for that position. However, it is also clear that for the other positions there is good agreement between the measurements and the simulations.

V.5. Estimation using personal dosimeters
Four passive personal dosemeter types were used in these measurements as well as one active design (Figure 5.29):

- Landauer Neutrak® chemical etched track dosemeter (CETD)
- PHE electrochemically etch track dosemeter (ECETD)
- Thermoluminescent albedo dosemeter (TLAD)
- Chemically etched track dosemeter with thermal TL element (CETDTL)
- Thermo-Fisher EPD-N2 active personal dosemeter (APD)

The aims of the measurements were three-fold:

- Determine the accuracy of personal dosemeters in the workplace
- Provide supporting evidence for the direction distribution of the field
- Allow the merits of the PODIUM approach to be compared to the state of the art using physical personal dosemeters

![Image](https://www.landauer.com/sites/default/files/product-specification-file/Neutrak_0.pdf)

**Figure 5.29.** Personal dosemeter exposures in reference positions

All five dosemeter types were placed as close as possible to the centres of the front faces of ISO slab phantoms, located at various positions (A, B, C, D, E and F) and orientations within the field; in all cases, the front face was identified as that closest to the source. In a first experiment, two slab phantoms (positions A
and C) had their front faces ‘covered’ by 16 PHE dosemeters, to check for dose gradient effects. Dosemeters were also placed on other sides of the phantoms to estimate direction components of the neutron distribution.

The positioning and results from the 16 PHE dosemeters exposed at positions A and C are shown in Figure 5.30, given relative to the reference $H^*(10)$ value at those positions; although not interpretable as a direct comparison, use of this normalization permits a useful comparison. In both cases, it is seen that the dose rate increases from top to bottom and from left to right, as expected from the survey instrument measurements. Overall, there is up to a factor of 2 difference between different positions on the same phantom for position A due to spatial dose rate gradients. This has to be kept in mind when comparing the personal dosemeter results. However, it is noted the typical uncertainty expected for the PHE PADC dosemeter is ~20% for a repeated measurement (28). Nevertheless, it demonstrates a weakness in single point-of-test dosimetry, and in turn a potential advantage of the PODIUM approach.

![Figure 5.30. Position and results from the 16 ECETDs ‘covering’ the phantom front face.](image)

Figure 5.30 shows the results of the five dosemeter types at positions A, B, C and D, and Figure 5.32 provides data at E, F and G, with all results again normalized to the respective $H^*(10)$ value. It is seen that:

- TLAD provides a low result in most cases; although this is not strictly an under-response, due to the normalization to ambient dose equivalent rather than personal dose equivalent: however, for pure frontal exposures the two quantities might be expected to be broadly similar.
- APD also provides a lower value at locations A, B and E when placed on the front of the phantom, but higher values when placed on the right side of the phantom at locations B and G and also at location G when placed on the left or back.
- CETDTL also provides a high value when placed on the right side of the phantom at location B, for which one ECETD recorded a zero value, likely due to a processing error.
- All dosemeter results were low at location F, for which the phantom was orientated at 45° to the flask, but of course the $H_p(10)$ response of a dosemeter is expected to be lower than $H^*(10)$ for acute angles > 0°.
- Low results were also found at location G, likely due to the same reason and attributable to neutron scatter from the wall adjacent to that position.
Overall, the direct (i.e. ‘frontal’) dose component was found to be dominant in all cases, as anticipated. Moreover, the reduction in $H_p(10)$ with angle relative to $H^*(10)$ is also expected. The trends and comparisons in Figures 5.31 and 5.32 are as expected: ECETD and CETD give $H_p(10)$ results that are typically within 40% of the $H^*(10)$ value, and generally consistently lower; the results from CETDTL and APD are more variable with location; and TLAD appear consistently low. The results of these 5 routinely used well established personal neutron dosemeters differ with a factor of 4 in our realistic field. This type of variability once again indicates the potential power of the PODIUM approach, given the current limitations of both the operational dose quantity and the dosemeters used to evaluate them.
After simulating the neutron energy spectrum and $H^*(10)$, the $H_e(10)$ was also modelled. This was achieved by putting slabs of ICRU tissue in the model at the locations in which the ISO water-filled slab phantoms were exposed. The established method of Siebert and Schuhmacher (10) was used.

Figures 5.31 and 5.32 also show these results from MCNP simulations. Considering the expected spread between the personal dosemeters due to imperfect response and spatial gradients, one cannot expect perfect agreement between the simulations and the personal dosemeter measurements. However, one can see that the order of magnitude and trends observed in the simulation results are very much in line with those observed in the personal dosemeter results. This gives again strong confidence in the MCNP simulations.

V.6. Comparison with effective dose

The mapping of the effective dose rate follows the same general procedure as that performed for the PHE Calibration Laboratory and described in detail in WP1. As before, a ‘spectral’ approach is adopted, in which a family of cones are defined on angled planes to allow the various angle components of the fluence-energy distribution to be determined at each location of interest. These angle components are convolved with appropriate fluence-to-effective dose conversion coefficients, which are binned using a suitably fine energy grid, and then normalized and summed to determine the effective dose rates for individuals located at those positions and orientated in various directions.
To generate the effective dose rate map in the PHE field, two cones of half-angle 67.5° were defined with their axes vertical to determine the Semi-Inferior Isotropic (SI-ISO) and Semi-Superior-Isotropic (SS-ISO) components, and 8 tangential cones of 22.5° half-angle were defined with their axes horizontal and at a height of 1.25 m from the floor; the contributions from the 8 horizontal cones were then weighted by a normalization factor (~1.26×) to ensure that the full 4π solid angle was accounted. However, one departure of the SCK•CEN exposure scenario from that at PHE is that its field contains directional components in non-horizontal planes, specifically ‘upwards’ exposures for individuals standing close to the fuel flask, which was on the floor. So, although the general approach was the same in both cases, this condition necessitated three modifications to the method employed at PHE:

- Fluence contributions in directions with vertical components needed to be calculated. Specifically, this led to eight additional planes and cones at each location being defined, which were directed downwards at an angle of 45°. These cones were distributed rotationally uniformly, relating to individuals facing in the same eight directions as used for the eight horizontal cones. To avoid overlap with each other and the eight horizontal cones, the half-angles of these cones had to be reduced to ~16° (~sin⁻¹ (π/8√2)), with the normalization factor then modified accordingly to account for the fluence ‘missed’ between the cones.

- Additional fluence-to-effective dose conversion coefficients had to be calculated that corresponded to the eight ‘upwards’ exposures.

- The opening angle of the ‘lower’ vertical cone, intended to determine the SI-ISO component of effective dose, also had to be reduced to avoid any double-counting of the fluence tallied by the eight new cones.

These simulations are still on-going. The above process will only provide effective doses per neutron emission, which needs to be normalized either to known parameters about the source or to measured benchmark data. Results from the effective dose rate mapping will therefore be obtained when the full validation of the Monte Carlo model is complete, via experimental and computational spectrometry. Once this is achieved, the map will be utilized to facilitate dose calculations from the people tracking.

V.7. People tracking

In the case of the neutron workplace at SCK•CEN described here, the use of the single camera IPS was sufficient given the size of the grid and being in an indoor facility. The camera was installed outside the grid as shown in Figure 5.33, where a person can be fully tracked inside the grid.
Figure 5.33. Location of the Kinect shown in the red circle

The calibration software was used to locate a reference point in the workplace from the camera coordinate system. This together with the rotation angles of the Kinect camera allowed to define the coordinate transformation of the tracked skeleton joints from the Kinect coordinate system to the lab coordinate system.

A Python script was developed that allows automatic calculation of the monitored worker dose by using the tracking file from the Kinect and the dose rate map from the simulations on the grid as input. A selection of the skeleton joint coordinates is taken from the tracking file and converted to the lab coordinate system. From these skeleton joint coordinates to position of the worker in the grid and the orientation towards which the person is facing are calculated for each time frame. This position and orientation is then matched with the appropriate dose rate during this time frame from the simulated dose rate map. The doses from all time frames are added together to calculate the total dose.

Figure 5.34. The calibration software used to get the coordinates of a reference point
The skeleton tracking was tested during the measurement activities (Figure 5.35). The recorded sequence simulated realistic actions of a worker moving around the flask and crouching. A dose of 7 µSv was calculated based on the simulated H*(10) map for 10 minutes of monitoring. Comparing this with the typical doses observed with the personal dosimeters worn by the staff involved in the measurements, this value can be considered as realistic. A direct comparison was not possible because the daily doses were too low for an accurate measurement with the personal dosimeters. For the future it would be even better to use the calculated effective dose rate map for this calculation. However, this is not yet available for the SCK•CEN workplace field.

VI. How well can we perform online dosimetry in workplaces now?

The two fields used in the PODIUM project have demonstrated that the Monte Carlo side of online dosimetry for mixed neutron/photon fields is eminently feasible now in terms of setting up a dose map. There remain difficulties with performing full online dosimetry in terms of workplace calculation of effective dose, but these have been surmounted using the dose map approach.

The Monte Carlo solutions for the workplaces have been verified by spectrometry. The Monte Carlo does require pre-information in terms of the materials, geometry and source term, but these factors seem less crucial than the pre-information required for experimental spectrometry.

The verifications performed using neutron survey instruments show that the calculated field can be adequately verified using such instruments. However, the variation between instruments is considerable, and the results with some instruments clearly very poor. Correcting the readings for the energy dependence of response of the instruments improves the situation somewhat, but the direction dependence of response of the instruments is harder to take into account and hence could be responsible for the uncertainties.
Personal dosemeter results show that there is significant uncertainty on the results obtained even for long exposures in fixed locations. The results for tracking people using Kinect and a dose map show that very low effective dose exposures could be estimated, at levels that personal dosemeters cannot aspire to achieve. It appears from this pilot study that there could be significant gains in occupational dose estimation achievable now, because lower doses could be estimated, and the dose estimates could be made in terms of the protection quantity, effective dose, rather than the operational quantity, personal dose equivalent.

VII. What developments might be needed for real-time online neutron dosimetry?

The ultimate aspiration for online dosimetry is the real time transport of radiation from the source(s) to deposition of the energy in an organ or tissue in a realistic representation of a person. The radiation may travel directly from the source(s) to the body, or undergo significant scatter on its way to the body, and the radiation source could emit various particles via a variety of reaction mechanisms. Some of the particles emitted may be short range, but they can still generate longer ranged secondaries which would need to be considered.

PODIUM has sought specifically to address the issue of neutron rich workplaces. But workplaces with a significant neutron field will also include a significant component of dose from photons: the source is likely to emit primary photons, but neutrons also generate secondary photons via (n,γ) reactions. The ultimate solution should hence include calculation of the neutron and photon doses simultaneously, but in PODIUM we looked mainly at the neutron part in these mixed fields.

Monte Carlo calculations for neutron transport are known to be relatively slow and computationally demanding when compared to those for photons. This is true for several reasons, including:

- Neutrons are strongly scattered in the environment, which means that each particle history can be complex;
- Once thermalized the neutrons effectively diffuse “slowly” through a medium undergoing many computationally expensive elastic scattering interactions;
- The cross-section files are necessarily very large because of the wide energy range, number of different reaction channels and the strong variation with energy, especially where there are resonances;
- The large cross-section differences that are observed for different isotopes of the same element;
- Neutron workplaces can be very large in scale and the neutrons may have suffered many scattering events and a lot of attenuation before they get to locations where people may be.

Taken together, these effects make the computational problems for online dosimetry in mixed neutron-gamma fields more complex, both in terms of computation times and memory requirements. For these reasons, and because of difficulties with the definitions of the dose quantities, PODIUM has settled on a “look-up table” approach for mixed fields containing neutrons.

VII.1. Issues with effective dose and \( H_{p}(10) \)

In principle, if an anthropomorphic phantom can be translated through the Monte Carlo geometry in real time, and perhaps flexed into realistic postures, then the actual effective dose that is being received by an individual could be calculated as it happens. In practice, this is difficult for all radiation types but for mixed neutron/photon fields there are added complexities associated with the definitions of the dose quantities that make it hard to achieve currently.
There is one difficulty in terms of the definition of effective dose that applies to all radiation types: it is defined in specific anthropomorphic phantoms with sex-averaging. Specifically, ICRP (29) defines effective dose as an average of values calculated in the reference male and female adult phantoms (30): this definition has been used in the calculation of the reference effective dose conversion coefficients (15). However, the reference values only consider monoenergetic exposures to single radiation types in a vacuum for well-defined geometries. Calculating effective dose for these simple fields and geometries is much less complex than doing it in a simulated workplace. For pure low linear energy transfer (L) fields, composed of photons and electrons, the scoring of the absorbed dose in a phantom is all that is required to generate conversion coefficients for any of the relevant dose quantities. This is because the radiation weighting factor, \( w_R \), and the quality factor, \( Q(L) \), are both 1 for all energies. Consequently, both effective dose and personal dose equivalent can be calculated for workplace scenarios where the penetrating radiation is dominated by photons, though whether or not the latter quantity is truly desirable may be field-dependent because \( H_p(10) \) can be a poor estimator of risk for individuals not exposed from the front. For neutrons, however, both the \( w_R \) and \( Q(L) \) are energy dependent, with the absorbed dose being weighted either by a \( w_R \) value (for effective dose) determined by the energy of the neutron that entered the phantom, or by a \( Q(L) \) (for dose equivalent) that is dependent on the energy of the charged particles released at the point of interaction.

The energy-dependence of \( w_R \) causes problems for the Monte Carlo calculation of effective dose in non-monoenergetic fields (i.e. in all realistic workplace fields) because the energy of the neutron that entered the body may be different from the energy of the neutron that is interacting at a given point-of-test (e.g. in an organ or tissue). Additionally, any secondary photons that deposit dose in the body should also have the \( w_R \) of the originally incident neutron applied to them. This causes difficulties, since for a particle tallied by the Monte Carlo code there is no simple method of ‘retrodicting’ the energy that the neutron had when it was originally incident on the body, such that the correct \( w_R \) may be identified and applied. This is a seemingly intractable problem for voxel phantoms in complex geometries that prevents effective dose from being calculated in distributed energy fields. This, as well as computation time issues, is the reason why PODIUM has favoured a look-up table approach for neutrons. All options for real time voxel phantom calculations are hence more complex because of the need for a two-step process, whereby the fluence of the field is resolved in direction and energy before effective dose is calculated by applying precalculated energy and angle dependent fluence to effective dose conversion coefficients.

Calculation of \( H_p(10) \) for neutrons is simpler, because there are approximation methods to generate dose equivalent (10) and some Monte Carlo codes have inbuilt \( Q(L) \) modelling (21). In a mixed field the total \( H_p(10) \) can be scored accurately within the phantom in a full neutron-gamma Monte Carlo calculation, but the separate neutron and photon contributions will be incorrect because whilst \( n\gamma \) reactions within the phantom should contribute to neutron \( H_p(10) \) they will actually be scored as a part of photon \( H_p(10) \). However, this conceptual difference would not matter for an operational online dosimetry system where only the total \( H_p(10) \) would be of importance, because the underestimate of the neutron \( H_p(10) \) would be exactly balanced by the overestimate of photon \( H_p(10) \). Nevertheless, and as mentioned previously, \( H_p(10) \) is a poor estimator of risk in some fields, such as when exposures are predominantly from behind (PA) or the sides (LLAT and RLAT), so its relative ease of calculation compared to \( E \) would be outweighed by its inaccuracy of risk estimation. Calculation of \( H_p(10) \) may therefore not be viewed as adequate for online dosimetry, though it is noted that similar problems also arise for physical dosimetry in such cases if the dosemeter is worn on the front of the individual. The ICRP and ICRU might adjust the definitions of the dose quantities in the future in a way that makes online dosimetry easier or more bespoke to a given individual. ICRP have
already published a consultation on environmental dosimetry that does not restrict the calculation of effective dose to the reference phantoms, though they maintain the sex averaging. For online dosimetry there would therefore be the potential to choose a phantom that provided a better description of the exposed person than is currently allowed by ICRP (29), such as through the use of larger or smaller reference individuals. However, for an online dosimetry system to be acceptable to the ICRP it may still need to produce sex-averaged results, unless ICRP modified their definition of effective dose. Alternatively, it may be considered that the uncertainties associated with using a male or female reference phantom are small compared to the uncertainties associated with the use of personal dosemeters, so sex-averaging is of secondary importance. This applies as much to mixed photon-electron fields.

ICRP currently have a consultation underway on the use of mesh-type reference computational phantoms (MCRPs) as a potential alternative to voxel phantoms. These are more flexible in terms of posture and size than voxel phantoms and might offer faster computation. However, in the draft document ICRP do not recommend that these should replace the reference voxel phantoms. It is intended that reference MCRPs will be made available with the published report for use with MCNP6 (21), PHITS (31) and Geant 4 (32). Already MCRPs have been used to generate alternative conversion coefficients for external exposures from photons, electrons, neutrons, protons and helions (33;34). They have been used in WP2 of PODIUM for photons only and do offer the potential for easier and more accurate real time Monte Carlo calculations in the workplace.

Changes to the protection quantity could also potentially involve a return to an effective dose equivalent type of definition, which ICRP have already recommended for astronauts (35): this could be scored relatively easily by all the main Monte Carlo codes because the energies of the particles at the scoring location would determine the contribution to equivalent dose, not the energy of the neutron as it enters the body. Such a change would make real-time online dosimetry for neutron effective dose equivalent easier to implement as a one-step process.

There are also proposed changes to the operational quantities (36), which could impact on online dosimetry. The current proposal to replace personal dose equivalent with a quantity personal dose might make the process online dosimetry simpler: personal dose is defined using the ICRP reference phantoms, but it is a property of the field at a point. There is some lack of clarity about whether the new quantity would be “receptor present” or “receptor absent”, which does affect the ease with which it could be calculated. But if the quantity is receptor absent, then the field at a point could be scored and energy and direction dependent conversion coefficients based on effective doses could be applied. Real-time calculation of personal dose could therefore be achieved without the difficulties associated with identifying the correct \( w_{kj} \), and yield results that do not possess the inadequacies of \( H_{p}(10) \) for highly oblique exposures. Conversely, if it is receptor present, the reference anthropomorphic phantoms would need to be introduced into the model, rather than a simple slab of ICRU tissue as is the case for personal dose equivalent, which would lead to the same, or if not harder, difficulties as those currently manifest for real-time calculations of effective dose.

VII.3. How much radiation?
It has already been highlighted that for real time Monte Carlo the speed of the calculations is a critical factor; this is especially so for neutrons, which are particularly computationally demanding. The following analysis is intended to provide a handle on the computational resources that would be needed to perform calculation in real time, though obviously there are several caveats to this. Firstly, any observations that can be made are dependent on processor speed and the acceleration methods (e.g. variance reduction techniques) that
are available. Secondly, the scale and complexity of the workplace will also be key, because the transport of the neutrons (and photons) to the location of the person might consume a lot of the computing power, even before the dose deposited in the phantom can be computed. Finally, with the person moving within the workplace, any variance reduction would need to be reoptimized as they move, or it would be unable to accelerate the calculations significantly. So, whilst it is useful to estimate what is required to get statistically valid results, and to assess whether it is feasible to do the calculations in real time, such estimates will inevitably be imprecise and strongly dependent on the workplace.

Personal dosemeters often have reporting thresholds around 0.1-0.2 mSv integrated over wear periods of weeks or months, and poor statistical precision even for higher doses. Online dosimetry may aspire to do better, perhaps obtaining a statistically valid result for a single entry to a workplace. Such entries may last several hours, but the focus for online dosimetry systems could be on short entries into high dose rate environments. This therefore sets a benchmark for the current analysis: in general, the dose received by an individual over a shift is most likely all that is required to be recorded with acceptable statistical precision. Of course, statistically robust instantaneous estimates would also be important if the online dosimetry system were to operate with an alarm capability, for example to detect dose rate ‘spikes’, but this circumstance is not considered further here.

Neutron fluence to effective dose conversion coefficients range from about 10 pSv cm$^{-2}$ for thermal and intermediate neutrons to 300 pSv cm$^{-2}$ for fast neutrons. As a result, it is necessary to have about $10^9$ thermal neutrons or $3\times10^7$ fast neutrons incident on the individual per square-centimetre to produce a dose of 1 µSv. It follows that for a dose rate of 1 µSv h$^{-1}$ to be received, a fluence rate of about $10^4$ cm$^{-2}$s$^{-1}$ would be required at the location of the individual. However, many more neutrons would have to leave the source to achieve this fluence rate at the location of the person.

Consider simulating such a scenario, and for simplicity assume that the source emits isotropically in vacuum. Assume also that an individual were one meter from this source for only 1 second, before moving away elsewhere. Additionally, assume that the fluence from the source at 1 m is to be determined in the Monte Carlo calculation using a tally with a cross-sectional area of 1 cm$^2$, orientated perpendicular to a radius of the sphere centred on the source. Finally, assume that the calculation is to be performed on a single CPU core. Then, for the online dosimetry system to be effective, it would have to correctly estimate, within an acceptable degree of precision, the true dose rate to the individual to within just one second of CPU time. For simplicity, and without loss of generality, let this acceptable degree of precision be ±10 %.

In such a circumstance, only 1 in $125664$ particles ($=4\pi\times(100)^2$) that are emitted from the source would on average be scored, giving a fluence of $\sim 7.96\times10^{-6}$ cm$^{-2}$. Moreover, if $125664$ particles were simulated in the Monte Carlo calculation, the statistical uncertainty on the result would be of the order of 100 %, because it could be expected to follow a Poisson distribution and hence scale broadly with the square-root of the number of particle tracks. To achieve the desired statistical precision of 10 %, $100\times$ as many particles would need to be simulated, i.e. $\sim 1.3\times10^7$. To perform real-time dosimetry in this case, the Monte Carlo code would therefore need to simulate this number of particle histories per second. Of course, this analysis is for a highly simplified scenario, and neglects in- and out-scatter as well as the contribution from secondary particles, but the result of $\sim 1.3\times10^7$ s$^{-1}$ illustrates the general scale of the computational demands that would be required.

In the SCK-CEN realistic field the dose rate at Position C, the effective reference position, was about $10^{-15}$ Sv
per source neutron. This would hence require a fluence of about $10^9$ source neutrons to generate a dose of 1 $\mu$Sv. Using the MCNP model, about $2 \times 10^6$ source particles were started per hour, which in effect equates to a dose rate of about 2 nSv h$^{-1}$ in the Monte Carlo model. This calculation used some basic variance reduction by manually setting cell importances.

The inability to get neutrons to the scoring position at the same rate at which they get there in the real workplace is only a problem if such high particle fluences are required for acceptable precision in terms of the relevant dose quantities. In this respect $H^*(10)$ is the easiest quantity to model because there does not need to be any transport within a phantom at the point of interest. In this instance, the statistical uncertainty is $< 10\%$ for cpu$^4 > 25$ s (Figures 5.36 and 5.37) at Position C, which could be considered acceptable accuracy. To achieve approximately 5% statistical uncertainty requires cpu $> 100$ s which demonstrates the required acceleration for the SCK-CEN workplace that would be required to do the calculations with acceptable accuracy in real time. Running on three of the laptop’s four cores approximately cuts the cpu by a factor of 3 to give real time elapsed.

![Figure 5.36](image)

**Figure 5.36.** Convergence of the mean fluence result for Position C versus cpu elapsed. Uncertainties are the statistical standard deviation of the Monte Carlo result.

Much bigger reductions in overall CPU time may be possible if the modelling is performed on a PC-cluster with far more cores, if the calculations can be efficiently distributed across the cores. Such task-distribution may be performed either in parallel, where many cores are dedicated to a single calculation in order to greatly accelerate its completion, or staggered, in which different cores perform calculations for different steps of the tracked-individuals motion. As an example of the latter of these, if due to the individual’s motion, a new dose rate calculation is required every second, and if each dose rate calculation takes 100 s, then Core 1 could perform the calculation for the individual’s position after 1 second, Core 2 could perform the calculation for the individual’s position after 2 seconds, and so on. Assuming that the cluster contains >100 cores, there would always be a free core available as required; such a mechanism would not quite calculate doses in real-time, having a 100s time-lag, but this would be sufficiently short in practice.

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4 Running on a Lenovo ThinkPad with an Intel® Core™ i7-770HQ 2.80 GHz processor with four cores
If just a voxel phantom were exposed to a plane-parallel, monoenergetic source, a computation time of tens of minutes would be required to obtain acceptable Monte Carlo precision on estimates of effective dose. For realistic geometries, in which the phantom would be inserted into a much larger Monte Carlo model of a workplace, the CPU required to yield organ doses to the same precision would be much higher as a result of an increasing number of particle histories ‘missing’ the phantom, and hence wasting CPU time. Additionally, codes can take significant times to initialize calculations that feature voxel phantoms, due to the $>10^6$ cells employed in their definitions, which in the case of MCNPX and MCNP6 is about $10^6$ s. This would be a fundamental limitation if a paradigm were envisaged in which a voxel phantom were to be moved within the model of the room geometry in a way that matched the motion of the tracked individual, leading to an unavoidable additional delay in performing that calculation in genuinely real-time.

The statistical precision required for a specific location and orientation may not be so great, because the combined results for a person moving through a geometry will have better statistical precision than the results for each calculation. This needs to be investigated for individuals tracked through a geometry, but the stopping and restarting of the calculations as the person moves will also incur additional CPU demands.

**VII.4. Which Monte Carlo codes?**

Some of the most widely used Monte Carlo codes do not transport neutrons (37; 38) so they will not be useful for online dosimetry in mixed neutron-gamma fields. There are, however, several well established codes that do neutron and photon Monte Carlo transport, including MCNP6 (31), MCNPX (20), GEANT 4 (32), PHITS (31) and FLUKA (39). Each of these is established as being able to produce results with acceptable accuracy, though all can produce poor results when not in the hands of an expert user (40; 41).

All these codes can be used in complex geometries and with voxel phantoms, so in principle online dosimetry could use any of the codes that are capable of transporting neutrons. They are all relatively similar in terms

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5 On a Lenovo ThinkPad with an Intel® Core™ i7-770HQ

6 Again, on a Lenovo ThinkPad with an Intel® Core™ i7-770HQ. When using the default settings, initializing the voxel phantom takes MCNP 6.1 about 60 s and MCNP 6.2 about 45 minutes, but workarounds are readily available.
of computational speed, except where the use of mesh phantoms is concerned:

- Geant 4 took about 1-30 minutes to achieve 2% uncertainty for photons of varying energy, and 2-30 hours for neutrons, depending on the neutron energy
- PHITS was 3-20 times slower than Geant4 for photons and electrons but 2-8 times faster for neutrons
- MCNP6 required run times 3-4 times longer than Geant4

These data are for a single 2.8 GHz processor using a single core, so acceleration is possible. However, it can be anticipated that by the time ICRP adopt mesh phantoms on radiation protection, the codes will all be able to deal with them in an efficient manner.

**VII.5 Can calculations be accelerated?**

Variance reduction methods can be applied effectively when calculating the field at a location, with there being many options within the available codes. Some of the methods are definitively two step, MCNP ‘weight windows’ being a prime example: a Monte Carlo run is first performed to determine the optimum weight windows map, before then applying this map to the subsequent full simulation. Consequently, it would be very complex to apply this in real time.

An additional difficulty for online dosimetry, where Monte Carlo proceeds in real time as the person moves through the geometry, is that the variance reduction would need to be continually reoptimized in synchronicity with the concurrent motion of the tallying volume within the model. This may limit the options for accelerating the calculations by using variance reduction methods. However, one option might be to surround the tallying volume with layers of ‘dummy cells’, of increasing importance with proximity to the tally, that move with it. Such an arrangement could be controlled by automatically editable subsidiary files that are external to the main MCNP input file, so that the variance reduction remains relatively optimized as the person moves.

Accelerated processing using graphics processing units (GPU) that are being investigated in PODIUM WP4 are currently limited to photons/electrons because they are only implemented in the Penelope code which does not transport neutrons, and the memory requirements of neutron cross sections cannot be applied when using GPU.

Using multiple cores in PC clusters can significantly accelerate calculations, and there are currently such clusters with large numbers of cores. If MCNP can be configured so that it can run a calculation spread across multiple cores, then the accelerations required for modelling $H^*(10)$ and $H_p(10)$ in real time seem feasible. It would perhaps be more realistic to run computations on a single core as a person moves through the geometry, opening a new calculation on a different core as the person moves. Real time calculations could then be achieved, albeit with a time delay for the calculation for each new position/orientation mapped. If the result for the dose was delivered after the shift was completed, that delay would not be a problem, assuming that the ALARP principle were being followed in the workplace.

**VIII. Summary and Conclusions**

Mixed neutron/photon fields were identified as an area where online dosimetry might be a very useful technique, but also one where there could be significant problems. The success of this feasibility study would depend on the selection of appropriate workplaces in which the techniques could be developed. The

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7 [http://www.icrp.org/docs/TG103%20Report%20for%20Consultation%2020180906.pdf](http://www.icrp.org/docs/TG103%20Report%20for%20Consultation%2020180906.pdf)
The calibration laboratory at PHE was always envisaged as the first stage of this testing process, but the selection of a real workplace was anticipated as being more problematic. Many sites were contacted, and all expressed interest, but the facility at SCK•CEN was the most promising for a feasibility study. These two fields turned out to be ideal for this testing, with relevant energy distributions and significant dose rates. The dose rates were not so high that the researchers would receive large doses setting up the PODIUM system. The level of interest from nuclear sites was indicative of the perceived value of online dosimetry for such workplaces.

Different approaches were needed for the simulated workplace and the real workplace, because the source term was very well known in the case of the simulated workplace but was not for the real workplace. Evaluation of the Monte Carlo model was a crucial aspect of this work package, because a poor model will impact badly on the accuracy of an online dosimetry system. Two methods were proposed: experimental spectrometry and surveying using neutron survey instruments. The first of these proved a useful aid to checking the Monte Carlo spectra, but in practice, the Monte Carlo results were more satisfactory for both sites, which is a strong endorsement for online dosimetry in such fields. The use of survey instruments was an important validation of the dose rates, but such instruments have energy and direction dependences of response. However, for both fields it can be concluded that the Monte Carlo model is accurate for $H^*(10)$ to within about 15%, which in the context of conventional personal dosimetry, where responses need to be in the range 0.5–2.0, is good performance.

Personal dosemeter exposures were performed for comparison with the online results. These were not used as validation of the Monte Carlo because personal dosemeters are not accurate enough to validate the results. This provided an almost unique test of personal dosemeters in a workplace, because generally reference $H_p(10)$ values are not available. The personal dosemeters were found to show significant variations in their readings for the same exposure, so it is evident that conventional assessments of personal dose equivalent are subject to considerable uncertainty. Online dosimetry, by making direct estimates of effective dose, offers significant potential for better estimates of workplace risk.

To obtain estimates of effective dose in a neutron-rich workplace has some computation time problems, but the definition of effective dose poses greater difficulty. These issues make direct estimate of real-time neutron effective dose in the workplace via computations in anthropomorphic phantoms unfeasible at present. To overcome this, innovative methods have been developed to produce an effective dose map for neutron workplaces. These novel methods are one of the main achievements: effective dose rate maps for location and orientation were generated for use with people tracking. Applying these dose maps yielded effective dose estimates of a few $\mu$Sv, whereas personal dosemeters generally have reporting thresholds of 100 $\mu$Sv or higher, with good dose estimate precision only being achieved above about 1 mSv.

PODIUM has demonstrated that the look-up table approach for mixed fields is feasible and offers the potential for significantly more accurate assessments of risk in neutron-rich workplaces. This innovative method was required because it was recognized from the outset that neutron effective doses could not be modelled in real time in complex geometries using voxel phantoms in the Monte Carlo model. Taken in isolation, the computational advances for real time online dosimetry estimations of effective dose look feasible if computations can be efficiently spread across many cores. Even if the computation cannot be split between multiple cores efficiently, then the use of individual cores for each location/orientation combination should be eminently feasible, even if it does not deliver real time results. However, whilst they are computationally feasible, fundamental difficulties still exist in applying the correct $w_R$ in such calculations.
The conceptual mis-match between effective dose and what is feasible in Monte Carlo looks hard to resolve without either: changes to the definition of the protection quantity; or enhancements in the Monte Carlo codes that enable them to weight the dose deposited by a given particle by a factor associated with the energy and type of the particle that entered the body. This problem seems harder to resolve than the computing power issues. However, the innovative method of calculating effective dose that has been developed in this work package offers the potential for improved risk estimation in mixed neutron-photon workplaces.

IX. WP5 References

WP 6: Dissemination of the project results

A dedicated Work Package (WP6) was set-up for the dissemination of the project results. The main objective of this WP was to stimulate the optimal application of the ALARA principle in various workplaces for the planning of occupational exposure as well as the education of exposed workers. Moreover, an exploitation plan for the future development of the project results was set up.

In order to accomplish these objectives the following tasks were elaborated:

- to seek advice for the orientation of the project by setting up an advisory board,
- to set-up an exploitation plan for the developed applications,
- to explore the possibilities of setting approval criteria for online dosimetry as legal dosimetry,
- to present the results of the project through a workshop,
- to participate in national and international conferences, workshops, fora and social media networks.

Task 6.1: Advisory board set up

Since PODIUM project and its approach is very innovative for individual dosimetry, an advisory board was established to give strategic input and guidance to the project partners by providing perspectives and feedback on the project and giving valuable advice on the future use of the applications and results developed within the project.

The board members that accepted the invitation to be part of the Advisory Board are:

- An Fremout from Federal Agency for Nuclear Control (Brussels, Belgium)
- Stefan Mundigl from European Commission (Luxembourg, Luxembourg)
- Shengli Niu from International Labour Office (Geneva, Switzerland) and
- Volodymyr Berkovskyy from Ukrainian Radiation Protection Institute (Kyiv, Ukraine)

Upon their acceptance they were informed about the progress of the project and invited to a meeting with the WP leaders. A detailed discussion was held afterwards. The main issues and input from the Advisory Board were the following:

- To use the project results also as “ALARA tool”: The tool could be applied afterward, in real time and beforehand. It would also be useful as an E&T tool, e.g. by adding virtual sources to real movements. If colours could be used it could show the operators’ doses visible in real time.
- Approval criteria for dosimetry system: To extend PODIUM application as dosimetry system legally approved, there should be, based on current basic safety standards, some kind of measurements and verification and not only simulations.
- Practicalities for interventional cardiology and mixed gamma-neutron fields: Considering the practical aspects, some problems may arise, such as sterilization in the interventional rooms, the presence of electrical cables and others. When placing the cameras inside the workplaces all these factors have to be taken into consideration. Another important and sensitive issue will be the protection of the patient, whilst being recorded by the cameras placed in the interventional workplace. In general, privacy tasks need to be arranged before setting up the online application.

Detailed minutes of the meeting with the Advisory Board were kept so that all partners were informed of their comments and more specifically about their ideas on the problems discussed and the possible solutions.

Close contact with the Advisory Group members was kept and they were invited in the project’s workshop in Athens in November 2019 to participate in the round table discussion.
Task 6.2: Exploitation plan

The vision of PODIUM was to improve personal dosimetry by the development of online dosimetry applications based on computer simulations without the use of physical dosemeters. It was envisaged that operational quantities, protection quantities and radiosensitive organ doses (e.g. eye lens, brain, heart, extremities) are assessed based on the use of modern technology such as personal tracking devices, flexible individualized phantoms and scanning of geometry set-up. Combined with fast simulation codes, the PODIUM application aims at performing personal dosimetry in real-time.

The main output of PODIUM is a set of software applications in which the occupational doses are individually calculated, instead of measuring them with one or more dosemeters. For this purpose, the position and movement of the exposed workers is captured using indoor positioning systems based on -time-of-flight sensors and then the calculation of the radiation field is performed leading to the dose of interest. A validation and proof of concept of the proposed methodology has been performed in two fields that could most benefit of the advantages of this methodology: interventional radiology and workplaces with mixed neutron/photon fields.

All project results have been collected and listed in Table 6.1. Most of the Project Results (PR) are linked to WP deliverables. However, there are some PR (such as no.4) which have been developed in our effort to overcome the pitfalls encountered during the project.

Table 6.1: List of project results

<table>
<thead>
<tr>
<th>Project Results (PR)</th>
<th>Title of the Result</th>
<th>Format</th>
<th>Short description</th>
<th>WP</th>
<th>IPR owners</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Phantom library</td>
<td>Software</td>
<td>Donna2018 (Donna with lead apron) Irene2018 (Irene with lead apron)</td>
<td>2</td>
<td>HMGU</td>
</tr>
<tr>
<td>2</td>
<td>Flexible phantoms</td>
<td>Software</td>
<td>Adjusted RAF phantom</td>
<td>2</td>
<td>SCK-CEN</td>
</tr>
<tr>
<td>3</td>
<td>Conversion coefficient set of data for IC/IR</td>
<td>Paper to describe the methodology of the calculation - Database with ASCII file</td>
<td>Conversion coefficients expressed in absorbed dose per fluence in mSv cm²</td>
<td>2</td>
<td>HMGU</td>
</tr>
<tr>
<td>4</td>
<td>Reduction techniques to reduce the number of look up tables</td>
<td>Paper</td>
<td>Estimation of conversion coefficients of smaller fields from those of a larger field via windowing</td>
<td>2</td>
<td>HMGU, PHE</td>
</tr>
<tr>
<td>5</td>
<td>IPS software for worker tracking 1 Kinect/2 Kinect</td>
<td>Software</td>
<td>Software for worker tracking, adapted to medical workplace</td>
<td>1</td>
<td>SCK-CEN, UPC</td>
</tr>
<tr>
<td>6</td>
<td>DCA (version X rays)</td>
<td>Software</td>
<td>Web application to do the dose calculation using as input the X-ray data and the worker tracking</td>
<td>3</td>
<td>UPC, SCK-CEN</td>
</tr>
<tr>
<td>Project Results (PR)</td>
<td>Title of the Result</td>
<td>Format</td>
<td>Short description</td>
<td>WP</td>
<td>IPR owners</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------</td>
<td>--------</td>
<td>-------------------</td>
<td>----</td>
<td>------------</td>
</tr>
<tr>
<td>7</td>
<td>Software (version mixed neutron/gamma)</td>
<td>Software</td>
<td>Structure of the web application, not customized for neutrons yet.</td>
<td>3</td>
<td>SCK-CEN, UPC, PHE</td>
</tr>
<tr>
<td>8</td>
<td>IPP</td>
<td>Software</td>
<td>Software to define and set-up a geometry for simulations</td>
<td>2</td>
<td>SCK-CEN</td>
</tr>
<tr>
<td>9</td>
<td>Validation results IC/IR</td>
<td>Paper</td>
<td>Validation of the dose calculation procedure by comparing it with measurements and with look up tables</td>
<td>4</td>
<td>SJH, LU, SCK, UPC, HMGU</td>
</tr>
<tr>
<td>10</td>
<td>Sensitivity study</td>
<td>Paper</td>
<td>Analysis of the influence of different radiation source parameters on operator’s doses</td>
<td>2</td>
<td>SJH, LU, SCK, UPC</td>
</tr>
<tr>
<td>11</td>
<td>Characterisation of PHE and SCK-CEN Workplace fields</td>
<td>Paper</td>
<td>Innovative methodology and computer models to derive the protection and operational quantities in workplace mixed neutron-photon fields</td>
<td>5</td>
<td>PHE, SCK-CEN</td>
</tr>
<tr>
<td>12</td>
<td>Conversion coefficients for neutrons</td>
<td>Paper</td>
<td>Conversion coefficients for the reference adult ICRP phantoms for the calculation of effective dose at angles intermediate to those calculated by the ICRP</td>
<td>2</td>
<td>PHE</td>
</tr>
<tr>
<td>13</td>
<td>MCGPU-IR</td>
<td>Software</td>
<td>Software to do fast MC calculation to obtain organ doses, effective dose and operational quantities in fluoroscopy guided procedures.</td>
<td>2</td>
<td>Based on the improvements in the open code MC GPU beta version (By A. Badal), New version property of UPC provided the origin is cited</td>
</tr>
<tr>
<td>14</td>
<td>Penelope/penEasyIR</td>
<td>Software</td>
<td>Software to obtain the energy fluence distribution, air kerma and $H_\beta(d)$ at a position of interest in fluoroscopy guided procedures.</td>
<td>2</td>
<td>Based on the improvements in the open code PENEOLOPE/penEasy (By J. Sempau), New version property of UPC provided the origin is cited</td>
</tr>
</tbody>
</table>
The heart of the exploitation objective of PODIUM project is the development of applications able to assess the doses of the workers in real workplace fields. Therefore, the exploitation plan addresses the following issues:

- The final products,
- The potential partners interested in further development of the products,
- Strategy for continuation of the project.

The final products depend on the way the tools are used and developed, such as:

- General training tool, where specific procedures can be practised and recorded without sources, to be analysed afterwards with virtual sources, and where the doses to the staff can be simulated. Training can be gamified to make it motivating, by adding a narrative thread of the simulation, a scoring system and instructional and feedback messages. Ergonomic issues in relation to the position and orientation of the staff in relation to the source can be simulated and validated with real data.
- ALARA tool: The application could include phantoms in the visualisation, making it more realistic. The visualization could be two-fold: on one hand, an animation of the room with the furniture and staff, on the other hand, a volume model of the phantom showing the computed distribution of doses. Similar simulations can be done in the mixed photon/neutron field.
- Dosimetry tool off line: To calculate the doses of staff after the work/procedure with possible specific modules for some practices such as IR/IC, NM.
- Dosimetry tool on line: To determine the doses during the practice, with some visualisation relating to possible specific modules for practices such as IR/IC, NM.

The above uses of the applications can be implemented in various fields:

- medical applications (fluoroscopically guided procedures, nuclear medicine practices,)
- industrial facilities (including radioisotope production),
- nuclear industry (including neutron dosimetry applications),
- space dosimetry.

Based on the above description of the applications and the exploitation potential the following InterCom (Interest in Commercialization) matrix is produced (Table 6.2). The evaluation of the TRL (Technology Readiness Levels) has been recorded in the Table based on the progress made up during the project. The TRL scale is a metric for describing the maturity of a technology. The scale consists of 9 levels. Each level characterizes the progress in the development of a technology, from the idea (level 1) to the full deployment of the product in the marketplace (level 9). At present the technology readiness level (TRL) is 3-5, depending on the application field, and requires a second phase to complete its demonstration to a TRL of 8 or 9.

For this second phase each partner’s position should be reflected. Since the Consortium, as per today, consists of a variety of partners, their interests are different: training, research, and commercialization. Possible continuation forms of PODIUM include: engagement of new scientific projects (for example EU-funded) or engagement of commercialization projects (like Fast Track to Innovation-FTI). Moreover, the results of the project can stimulate innovation and technological progress in industry and therefore, collaboration with industrial companies is also an option. Also, continuation on the partners’ own budgets is possible.

Regarding the potential partners, outside the project, needed for the development of the project this is also included in the intercom matrix (last column). From this it is clear that experienced partners in innovation and exploitation strategies should collaborate in a new consortium to ensure the introduction in the market of the PODIUM results.
Table 6.2: Interest in Commercialization Matrix (Exploitable results)

<table>
<thead>
<tr>
<th>Exploitable Result&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Title of the Result</th>
<th>Exploitation potential</th>
<th>Field of interest</th>
<th>Organisation contributed to the generation of this result during the project's lifetime</th>
<th>TRL</th>
<th>Expertise needed outside PODIUM consortium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Phantom library</td>
<td>Needed for further look-up tables</td>
<td>All fields</td>
<td>HMGU</td>
<td>TRL5</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Flexible phantoms</td>
<td>Potential use for any application with GPU, and for visualisation.</td>
<td>All fields</td>
<td>SCK-CEN</td>
<td>TRL5</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>IPS software for worker tracking 1 Kinect/2 Kinect</td>
<td>Software for worker tracking, adapted to medical workplace</td>
<td>All fields</td>
<td>SCK-CEN, UPC</td>
<td>TRL6</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>DCA (version X rays)</td>
<td>Software application in X-ray facilities used for the estimation of the doses of the exposed staff using as input the X-ray data and the worker tracking</td>
<td>Intervventional procedures (medical field)</td>
<td>UPC, SCK-CEN</td>
<td>TRL5</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Software (version mixed neutron/gamma)</td>
<td>Software to define and set-up a geometry for simulations</td>
<td>Industry and nuclear Industry</td>
<td>SCK-CEN, PHE</td>
<td>TRL3</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>IPP</td>
<td>Software application to define and set-up a geometry for simulations</td>
<td>Intervventional procedures (medical field)</td>
<td>SCK-CEN</td>
<td>TRL4</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>MCGPU-IR</td>
<td>Software application in X-ray facilities (one of the dose calculation methods)</td>
<td>Intervventional procedures (medical field)</td>
<td>UPC</td>
<td>TRL4</td>
<td>No</td>
</tr>
<tr>
<td>14</td>
<td>Dose calculation Penelope/penEasyIR</td>
<td>Software application in X-ray facilities (one of the dose calculation methods)</td>
<td>Intervventional procedures (medical field)</td>
<td>UPC</td>
<td>TRL5</td>
<td>No</td>
</tr>
</tbody>
</table>

<sup>a</sup>Number taken from Table 1 (Project Results)
Concluding, PODIUM is perceived as an innovative way forward. It is envisaged that the availability of individual dose data will increase awareness of radiation dose, improve compliance with radiation protection tools and assist with application of the ALARA principle. The PODIUM application approach has the potential to be brought to the market using it as a training tool or as individual dosimetry option. In the two year project, the consortium has already established some initial contacts with some commercial partners and there are Consortium partners willing to continue in order to collaborate and place the application in the market.

**Task 6.3: Establishment of approval criteria for online dosimetry as legal dosimetry methodology**

Another objective of WP6 was to stimulate the application of the PODIUM online dosimetry system as a tool for ALARA and training of exposed workers. Thanks to its graphic visualization capabilities, the dosimetry system developed by PODIUM can effectively enhance the awareness of exposed workers. However, the ultimate aim of PODIUM online dosimetry system is to be used, not only from the ALARA point of view, but also for quantitative dosimetry. Within this context an investigation has been performed for exploring the possibility of proposing criteria for a purely computational dosimetry system to be approved as dosimetry system for the estimation of the levels of occupational exposure. In order to achieve this, the general aspects in respective European and international standards for establishing a procedure of approving computational dosimetry as legal dosimetry have been collected as well as the various approval criteria in different countries.

For the collection of data related to the criteria used for the approval of dosimetry services the following data sources have been used:

- The European Directive for the establishment of the Basic Safety Standards, Euratom 59/2013 (EU BSS) [1]
- The recommendations of Radiation Protection 160 of the European Committee [2]
- The IAEA safety standards (GSR part 3 and GSG-7) [3,4] and
- The ISO 17025 standard [5].

Within the EU BSS [1] it is foreseen that any provider of dosimetry services shall be approved by the competent authority. The purpose of the approval procedure is to recognize and verify that a dosimetry service provider is technically competent and able to generate technically valid results. The procedure for approval is the same of passive and active dosemeters. For some categories of workers, it is sufficient to use computational tools to estimate the individual dose. For example, cosmic radiation fields in aircraft are fairly uniform and predictable. Computer codes have been developed for assessing the doses received by aircrew from cosmic radiation and have been validated against measurements. This methodology is also accepted for legal dose of record. Based on the EU BSS [1] “a dosimetry service means a body or an individual competent to calibrate, read or interpret individual monitoring devices, or to measure radioactivity in the human body or in biological samples, or to assess doses, whose capacity to act in this respect is recognised by the competent authority”. In this sense a computational dosimetry system, if performed by a dosimetry service, can be considered to fulfil this requirement.

Regarding the IAEA safety standards [3,4] “individual monitoring means the monitoring using measurements by equipment worn by individuals, or measurements of quantities of radioactive substances in or on, or taken into, the bodies of individuals, or measurements of quantities of radioactive substances excreted from the body by individuals”. In this sense the computational dosimetry system is excluded from the individual monitoring part since “measurements” are clearly required. It is of course a discussion point what exactly is considered as “measurement”. In PODIUM project, the doses are calculated based on measurements of the position of the worker, and based on measurements of the workplace field. This is done on an individual bases, so it is individual monitoring. Requirement 25 of IAEA safety standard [3] states that for the assessment of occupational exposure: “Employers, as well as self-employed persons, and registrants and licensees shall be responsible for making arrangements for the assessment of the occupational exposure of workers, on the basis of individual monitoring where appropriate, and shall ensure that arrangements are
made with authorized or approved dosimetry service providers that operate under a quality management system.” Again, it is said that individual monitoring is needed where appropriate. It can be interpreted that if computational dosimetry is better than “measurements” it could be used because it is more appropriate. But again, computation dosimetry, as proposed in PODIUM, can be considered as individual measurements of the doses, as long as it is performed by an authorized or approved dosimetry service provider. Moreover, based on article 41, paragraph 3 of the EU BSS [1]: “In cases where individual measurements are not possible or inadequate, the individual monitoring shall be based on an estimate arrived at from individual measurements made on other exposed workers, from the results of the surveillance of the workplace provided for in Article 39 or on the basis of calculation methods approved by the competent authority”. In this regard the computational dosimetry system can be used on the basis of calculation methods, if individual measurements are not possible or inadequate. In this case it can be argued as well, that if a computational system is better than a conventional one, it can be used instead of the conventional. From an overview of the regulations for a series of European countries that was performed within WP6 it was shown that the most commonly criteria used for approving the dosimetry services include:

- The development and implementation of a management system, which is based on the ISO / IEC 17025 [5],
- The participation in intercomparison exercises,
- The metrological traceability to a National Metrology Institute and/or a Secondary Standard Dosimetry Laboratory and
- The submission of the dosimetry data to the National Dose Registry.

The management system is a set of interrelated or interacting elements for establishing policies and objectives and enabling the objectives to be achieved in an efficient and effective manner. The only difference in the case of a computational dosimetry system with a conventional one is the process of the assessment of doses. If this is validated, then the criterion of management system is easily applicable in the online dosimetry systems.

The intercomparison (or interlaboratory) exercise is the organization, performance and evaluation of measurements or tests on the same or similar items by two or more laboratories in accordance with predetermined conditions. It is clear that the conventional way of performing intercomparisons that is used now for passive dosimeters cannot be used. However, it is possible to set-up other types of intercomparisons, specifically for computational systems, like it is done for computational codes for aircrew dosimetry.

Metrological Traceability: Based on ISO 17025 standard [5] the laboratory shall establish and maintain metrological traceability of its measurement results by means of a documented unbroken chain of calibrations, each contributing to the measurement uncertainty, linking them to an appropriate reference. The whole methodology of the computational dosimetry is based on a series of measurements that validate the applied method. This validation can be considered as assessment of dose levels against the conventional true dose taken from the conventional dosimeters in the reference conditions or by reference dose, if possible.

Record keeping and submission of the relevant record to the national dose registry: Regarding records keeping, the computational dosimetry system should be developed in a way to be possible to identify the various persons involved in practices with ionizing radiation with a specific identification number related to each workers.

Finally, the use of computational dosimetry systems to be used as official dosimetry service provider was also discussed in the 1st meeting with the Advisory Board. The following were the main conclusions of this discussion:

- Due to the fact that an individual monitoring system contains measurements, PODIUM dosimetry system cannot be similar to a conventional individual monitoring system and not to the one used for the calculation of the aircrew doses, where measurements cannot be performed.
Moreover, in the aircrew dosimetry there are no dose limits for the aircrew.

Regarding the approval criteria, the Advisory Board stick to the fact that an individual monitoring system should be based on measurements. However, PODIUM dose results are linked to measurements, so such a system could be accepted in the future.

Concluding, it can be argued that the computational method from the PODIUM approach can be considered as a “measurement of the individual dose”, in the way that is required in international standards. Therefore, a computational dosimetry system can be considered as an official dosimetry system for the estimation of the operational quantities. The computational dosimetry system should also be operated by an approved dosimetry service when certain criteria are met. These criteria include the verification of the methodology, the uncertainty estimation, the validation through intercomparison exercises, the record keeping and the management system of the provider, which can lead to a reasonable credible process of submitting the data to the respective national dose registry.

**Task 6.4: Preparation of a 2-day workshop**

Scientific dissemination of the PODIUM results was foreseen within the framework of the project, with main tool the organization of a workshop. The main objective of the workshop was to emphasize and to discuss the ALARA principle and to present the advantages of online dosimetry systems in routine practice. For better dissemination of the results it was decided to organize the workshop back to back with the European ALARA network (EAN). The EAN workshop was focused on innovative ALARA tools and their use in advancing Radiation Protection and ALARA principle.

The workshop was divided into 4 sessions, where the objectives, methodology, results and future work of each work package were presented and discussed.

The first session started with the general presentation of the PODIUM project. The presentation was focused on the framework, i.e the motivations that led to the accomplishment of this project, the objectives, the materials and methods used and the tasks of each one of the six work packages. Then the Indoor Positioning Systems (IPS) were presented with the use of single and multiple RGB-Depth camera systems to track all people in the operation room in order to provide with 3D position all the staff body parts in real time. The next presentation of the first session was focused on the use of the “look-up approach”. This task may provide fast dose calculations for workers moving in realistic fields using computational phantoms for various statures and postures and Monte Carlo methods for both photon and neutron radiation workplaces. The methodology that was followed allows the development of a library of pre-calculated conversion coefficients (look-up table approach) as an alternative method to fast online Monte Carlo calculations.

In the second session of the workshop the computational methods in regards to the Monte-Carlo tools and the computational human phantoms were presented. Individualized phantoms were presented for both online simulations and the look-up table approach. Within PODIUM, several phantoms were used for the calculation of different dose quantities. Computational phantoms from HMGU, namely REX and REGINA, were used in MC-GPU for the online simulation approach. Computational phantoms from HMGU, namely DONNA and IRENE, together with the RAF phantom of SCK•CEN were used to create the database of dose conversion coefficients for different postures and statures for the look-up table approach. To facilitate the modification of the posture of the RAF phantom, a user-friendly software was developed where the user can easily change the pose of the phantom and export it in either voxel or polygonal mesh formats for different MC codes. Moreover, the methodology of using Monte-Carlo codes for dose calculations was introduced. The use of three different Monte-Carlo codes was investigated for occupational dose calculations in interventional radiology fields: PenEasy-IR, MCNP and MC-GPU. The results of the first validation test performed in a controlled experiment at the hospital of Lund university in Malmö was presented where the personal dose equivalent \( H_p(10) \) measured by several personal dosemeters (EPDs and TLDs) was compared with simulations. The results showed good agreement between the measured \( H_p(10) \) and the calculated respective value of \( H_p(10) \) using PenEasy-IR, MCNP and MC-GPU.
The third session was about the development of the online dosimetry application and the application of PODIUM in IR/IC fields and in neutron fields. The first presentation of the session was on the application in IR/IC fields at the University of Lund in Malmö and at the St. James hospital in Dublin. Both hospitals had received positive feedback from the involved staff. The second talk was focused on the creation and developments of the online dosimetry tool. The last presentation was about the application of PODIUM in neutron fields.

In the fourth session, the first presentation was given by the invited speaker Prof. Jim Malone from the Trinity College of Dublin. The speaker introduced the audience to the concept of the value set of ethics that should be used in medicine. He emphasized that we must not just rely on our personal moral compass, but rather professional ethics values. The audience were given some real examples of when doctors and hospital management are faced with difficult moral and ethical questions. Prof. Malone spoke about the need to look carefully at privacy and ethics issues for the PODIUM type approach, to ensure that the concept of surveillance or tracking is acceptable to health professionals and patients.

The next part of the fourth session was a panel discussion with interaction with the audience. The panel members were from PODIUM, EAN and PODIUM’s Advisory Board. The invited speaker also participated in the discussion.

The first topic of discussion was the potential advantages of online computational dosimetry. From ALARA point of view the computed doses available in real-time is considered very beneficial, especially if it allows immediate feedback during a procedure which will lead to low doses. Furthermore, this has strong potential for training. The Advisory Board agreed that the PODIUM approach has great potential as optimization and training tool. It was also mentioned that accuracy is priority for a technique to become applied in practice. Jim Malone indicated that it would be useful for the staff report to include an estimate of the risk (in addition to the dose), because that is in the end what people want to know.

The next topic of the discussion was the feasibility of the PODIUM approach in medical field, nuclear and other industries.

The Advisory Group doubted whether computational dosimetry can legally be accepted, because computational dosimetry is performed and approved only when physical dosimetry is not possible or adequate. However, as a start, physical and computational dosimetry can be used in parallel and then computational dosimetry can be gradually introduced officially (similar to active dosemeters). Member from the audience stated that a physical measurements will always be necessary because computational dosimetry is limited by what is inserted into the model and, therefore, some accident scenarios might not be included in the model. The approach was considered interesting in order to reduce the number of dosemeters, but at least one dosemeter should still be used in addition to the computational dosimetry to avoid missing certain accident scenarios.

Ethical issues, together with legal issues, were topics of interest for the implementation of the PODIUM solution considered for the discussion.

The final talk of the PODIUM workshop was focused on a summary of the project achievements. It was concluded that the feasibility study by PODIUM over two years has been a success. The technology is now available for tracking people to be monitored, calculating doses in a fast way (using a look-up table approach/dose mapping or Monte Carlo calculation), at a rate of less than 30 s/event. Detailed and personalised phantoms are also available. PODIUM is a new tool for training and ALARA, to confirm which workers require official monitoring. Some limitations and challenges that remain were presented. Future work plans were described along with how PODIUM fits in with the TRL (Technology Readiness Levels) defined by H2020. Overall the conclusions of the project are very promising.

**Task 6.5: Scientific dissemination**

In order to have the PODIUM results disseminated all the members tried to participate in national and international conferences, workshops, fora and networks. Several presentations have been performed or are
to be performed in the coming period. The PODIUM group member have planned a number of submissions to scientific journals in 2020.

References for WP6


