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PAPER

Feasibility study of computational occupational dosimetry: evaluating a proof-of-concept in an endovascular and interventional cardiology setting

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Abstract

Individual monitoring of radiation workers is essential to ensure compliance with legal dose limits and to ensure that doses are As Low As Reasonably Achievable. However, large uncertainties still exist in personal dosimetry and there are issues with compliance and incorrect wearing of dosimeters. The objective of the PODIUM (Personal Online Dosimetry Using Computational Methods) project was to improve personal dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosimeters. Occupational doses were calculated based on the use of camera tracking devices, flexible individualised phantoms and data from the radiation source. When combined with fast Monte Carlo simulation codes, the aim was to perform personal dosimetry in real-time. A key component of the PODIUM project was to assess and validate the methodology in interventional radiology workplaces where improvements in dosimetry are needed. This paper describes the feasibility of implementing the PODIUM approach in a clinical setting. Validation was carried out using dosimeters worn by Vascular Surgeons and Interventional Cardiologists during patient procedures at a hospital in Ireland. Our preliminary results from this feasibility study show acceptable differences of the order of 40% between calculated and measured staff doses, in terms of the personal dose equivalent quantity $H_p(10)$, however there is a greater deviation for more complex cases and improvements are needed. The challenges of using the system in busy interventional rooms have informed the future needs and applicability of PODIUM. The availability of an online personal dosimetry application has the potential to overcome problems that arise from the use of current dosimeters. In addition, it should increase awareness of radiation protection among staff. Some limitations remain and a second phase of development would be required to bring the PODIUM method into operation in a hospital setting. However, an early prototype system has been tested in a clinical setting and the results from this two-year proof-of-concept PODIUM project are very promising for future development.

1. Introduction

1.1. Occupational dose monitoring for fluoroscopically guided procedures

The use of fluoroscopically guided interventions as an alternative to conventional surgery is increasing globally; however, it is well established that the procedures can result in occupational radiation doses, including eye doses, which are high enough to warrant concern [1–7]. Cardiology is one of the largest single users of medical radiation and complex percutaneous coronary interventions (PCIs) are associated with high radiation doses [8]. Some medical procedures require large amounts of radiation from lengthy fluoroscopy or multiple images, such as in vascular surgery where the use of fluoroscopy for endovascular aortic aneurysms repair (EVARs) is increasing, and radiation levels are similar to those in interventional radiology and interventional cardiology. The use of more complex endovascular devices, such as branched and fenestrated stents is likely to increase. These procedures are long and complex; requiring prolonged fluoroscopic screening [2].

The significant occupational exposures in these situations require the use of robust and adequate monitoring arrangements for workers [2]. Individual personal dose monitoring of radiation workers is essential to ensure doses are As Low As Reasonably Achievable (ALARA) and to ensure compliance with recommended or legal dose limits [4, 9, 10]. For interventional procedures, individual monitoring with passive dosemeters remains the most widely used option [3]. Depending on the monitoring programme in place, staff may be issued with a single dosemeter worn under the lead apron and another dosimeter worn at collar level. In view of the reduced threshold for radiation-induced cataracts, monitoring the eye lens dose is important for those involved in interventional procedures [2, 3, 11–13] and dedicated eye lens dosemeters may be recommended. It will also sometimes be appropriate to monitor hand doses, using a small ring-shaped dosimeter [3, 11]. However, large uncertainties still exist in personal dosimetry [3, 14]. There are also issues with compliance where dosemeters are not worn, and when multiple physical dosemeters are issued to interventionalists as described above, there is scope for them to be mixed up, worn incorrectly or lost [3, 15]. Improvements to the current approach which is based on individual personal dosimetry monitoring for interventional workers are needed [16].

1.2. Background to this study

This study is part of an EC-funded research project entitled Personal Online Dosimetry Using Computational Methods (PODIUM) with an overall objective of improving personal dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosimeters. The PODIUM application is based on an Indoor Positioning System (IPS) using a motion-sensing camera to track staff position and posture in the clinical room. The system uses the concept of 'skeleton' tracking to accurately predict the 3D positions of body joints in real-time. This is then combined with information on the radiation source and Monte-Carlo (MC) simulation codes to calculate occupational radiation doses [17, 18].

Some previous studies using MC simulation to evaluate the doctor's dose in Interventional Radiology are available in the literature [19, 20], including work published by the European Radiation Dosimetry (EURADOS) group [21–23]. These studies utilised MC codes to calculate doses at typical locations of the radiation worker in the scatter field. A further step in utilising MC for dosimetric calculations was attempted by Badal and Badano [24]. The main limitation of the system is the manual operations required to trigger the simulation based on predefined library of settings. Also, the system was not tested during a clinical procedure. The PODIUM type approach can in theory improve on previous work by determining the actual position of the staff accurately in real-time including the measurements of relevant organs such as the hands and the lens of the eye. The proposed PODIUM system had to be designed to meet the demands of the clinical environment and be feasible to use in hospitals. The radiation dose simulations must be accurate, at least within a factor of 1.5 recommended for dose measurements in ICRP 75 and found in routine use [5, 25]. Privacy and ethical concerns were highly relevant in this scenario with a camera monitoring movement in the room.

The aims of this feasibility study were to (a) compare calculated doses for staff with doses measured during patient procedures in a complex clinical environment and (b) explore difficulties and identify future needs for this concept in a hospital setting. In this paper we present the work done on the task of validating this proof-of-concept system in a clinical environment during patient procedures at St. James's Hospital (SJH), Dublin, Ireland. Three selected MC calculation codes are used to simulate occupational dose and compare it to dose measured with a physical dosimeter during interventional procedures on patients. This work is the second in a series of similar validation measurements performed at the Skane University Hospital in Malmo, Sweden, based on one experimental case and three clinical cases [26]. The three clinical cases in Malmo were performed in one interventional x-ray room with the camera in a fixed position in the ceiling

and the results obtained were promising, with differences between simulated staff radiation doses, in terms of the personal dose equivalent quantity $H_p(10)$ of the order of 30%–70% with similar levels of differences between measurements and simulations. In the more complex investigated case including ceiling-mounted radiation shields, this figure increased to over 100%. As discussed in the following sections, in SJH the PODIUM system was installed and tested in two different clinical rooms (endovascular and cardiac) giving a breadth of experience across clinical specialties in both hospitals.

2. Materials and methods

The feasibility study was focused on validating the proof-of-concept IPS and the developed MC calculation codes for use in interventional radiology/cardiology. Key parameters to be recorded in the clinical environment were: the dose per procedure ($H_p(10)$) to the staff member; the exposure parameters and other relevant data from the radiation source; motion tracking information of the exposed worker and also any Personal Protective Equipment (PPE)/radiation protection tools used during the case.

2.1. Measured dose per procedure ($H_p(10)$)

For each validation case, in order to compare with the simulated dose, the monitored worker (primary operator) was issued with an Active Personal Dosimeter (APD). This was worn above the lead apron at chest level. The APD used for this study was the Thermo MK2 EPD (Thermo Scientific, Germany). The uncertainty of this APD is 10% ($k = 2$). The position of the dosemeter on the operator was recorded in terms of general wearing position e.g. left chest, right chest, centre chest.

2.2. Radiation source

In SJH, the PODIUM system was installed and tested in two rooms. The first room (Endovascular operating theatre) is installed with a four-year-old Siemens Artis Q (Siemens Ltd, Erlangen, Germany) system. The second x-ray room was a Cardiac Catheterisation Laboratory fitted with a five-year-old Philips Allura FD10-10 Bi-plane system (Philips Medical Ltd, The Netherlands). The clinical case mix was chosen based on procedures that were typically of sufficient radiation dose (in terms of the validation statistics) and that were commonly performed around Europe in a similar manner. Endovascular procedures such as EVAR and angioplasty performed by Vascular Surgeons were selected, along with Coronary Angiogram and PCI procedures performed by Interventional Cardiologists. The clinical setting is a large tertiary referral teaching hospital with busy workloads. Procedures may require the presence of many staff in the room, including those from the surgical team, nursing, anaesthetics, radiography, and staff in training. This is relevant to PODIUM as it was known from preliminary tests that the IPS is challenged by complex installations where there are many staff members and large amounts of complex equipment present.

The age of the equipment is also of relevance. A key factor needed for PODIUM was the availability of a DICOM standard Radiation Dose Structured Report (RDSR). These RDSRs include metrics such as Kerma Area Product (KAP), as well as detailed geometric and technique information. RDSR outputs are required for interventional fluoroscopic equipment conforming to IEC 60601-2-43 [27] 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 information on the x-ray primary beam conditions, table positions, angulation, collimation and numerous other parameters.

Once an RDSR is available, even though it is a file with a defined standard and format (.SR), it can be converted into other file formats and the contents can vary. The RDSR may typically be available in .DCM or .XLS format and some manufacturers include fields that are omitted completely by other manufacturers, or present as an empty field. Some challenges were encountered with information missing or not included in the RDSR for example; the radiation field size was not always readily available in a standardised way due to the version of the RDSR software. Additionally, for the MC simulation, precise knowledge of the isocentre of the C-arm is required and the isocentre will move as the C-arm moves. The horizontal movement of the C-arm (along the length of the patient) was displayed in real-time on the TV monitor but not stored in the RDSR. Efforts were made to minimise the impact of this by recording C-arm position after significant movements were observed.

2.3. Time synchronisation

It is important to ensure synchronisation of the computer clock on the radiation source equipment (the x-ray system PC) with the IPS software (computer clock on the PC used for PODIUM tracking). The simulation depends on taking each irradiation event from the x-ray system RDSR and matching this (with an accuracy of 1 s) to the computer file tracking the position of the staff member. For the two rooms used in this study,

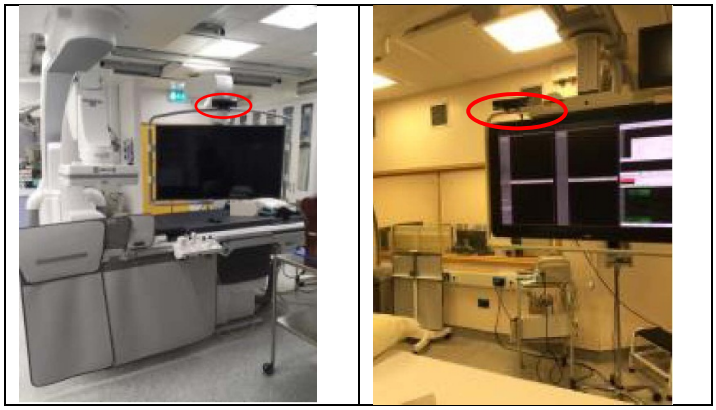

Figure 1. Location of camera installed in endovascular x-ray room (left) and cardiac cath lab (right).

both x-ray system clocks were set to a network time protocol server which is used for all hospital PCs. This ensured that all PC clocks used for PODIUM were synchronised to the greatest possible degree of accuracy.

2.4. Tracking of the radiation worker

A Microsoft Kinect™ camera was used for motion tracking in PODIUM as described in [17]. One camera was installed in each room, connected to a PC, and photos of the installed cameras are shown in figure 1. An RDSR file of every radiation exposure event (with a timestamp) is combined with the positional information (from the camera) of the staff member (at the same timestamp). This data is used in the MC software to simulate the scattered radiation at that time based on the exact position of the individual staff member.

In the endovascular theatre, choosing an ideal location for the camera was difficult due to the complex nature of the existing installation. The room is designated as an operating theatre, with few surfaces available to mount additional equipment. The camera was mounted on the large x-ray TV monitor. This was ideal in terms of achieving a good view of the main operator; however the TV monitor is not a fixed item and may be moved during cases affecting the calibration of the camera. Efforts were made to overcome this by carrying out calibration measurements using a calibration software tool developed by the PODIUM team, to record positional information if the TV monitor moved during clinical procedures.

It is possible with the Kinect™ to track up to six persons, however for this study only the main operator data was used for the calculations. The software body ID that is assigned to the main operator 'skeleton' can change during tracking. Therefore, the files that are created for each tracked person (6 files in total) are a combination of persons within the room and require filtering to locate the main operator body ID. This process was done manually for the first recorded cases based on observers' notes. However for later cases, the process was automated using a Python script to identify the body ID of the main operator.

For use in the endovascular operating theatre, a portable medical grade PC was used. Although it met the minimum operating requirements for a Kinect™, the performance of the portable PC was not optimal and on occasion the camera would lose connection and in this case tracking events were not captured. The size of tracking files was also considerable (averaging around 50 MB $\times$ 6 'skeleton' files for some procedures) and as such, suitable file storage and backup was required. For the Interventional Cardiac room, the camera was connected to a standard desktop PC positioned outside the patient environment at the operator's console.

2.5. Ethics and data protection

Motion tracking clearly involves monitoring or surveillance of persons in the room and this is a core concept of PODIUM. Prior to commencing this proof-of-concept in a clinical setting, the ethical, legal and data protection requirements were fully implemented. Hospital research approval was obtained and Research Ethics Committee approval was granted, specifically in accordance with the implementation of the general data protection regulations (GDPR) in Irish law for research studies. Patient and staff consent was obtained for all procedures and all RDSR files were anonymised. No persons are identifiable from the camera images and image storage was not required, only storage of the co-ordinates from the skeleton tracking.

2.6. Simulated dose per procedure using Monte-Carlo tools

As introduced previously, the PODIUM project aimed to establish new methods for personal dosimetry, without wearing individual dosimeters. In order to test the feasibility of the approach, experimental or measured values of $H_p(10)$ during clinical cases were compare to calculated or simulated values.

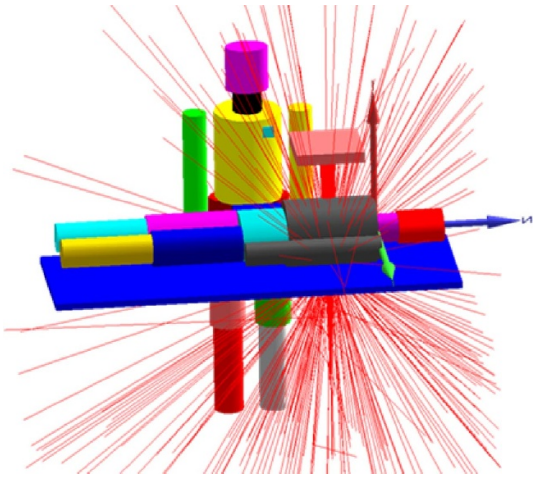

Figure 2. Simplified geometry used in MCNPX simulations.

The simulations for the PODIUM project were performed using three MC photon radiation transport codes: MCGPU-IR [24], PENELOPE/penEasyIR [28, 29] and MCNPx [30]. In order to compare calculated values with experimental ones, a normalisation to absolute values is required for each irradiation event. The normalisation factor is obtained from the ratio between experimental and simulated air kerma at a reference point [31]. The experimental air kerma was calculated using the KAP value which is a direct measurement using a physical KAP-meter located at the x-ray tube. The KAP meter undergoes routine quality control testing and has an accuracy of within 15%.

2.6.1. Monte Carlo N-particle (MCNP/MCNPX)

The Monte-Carlo N-Particle (MCNP) transport code system is a general-purpose MC code that deals with neutron, photon, electron, or coupled neutron/photon/electron transport [30]. MCNPX is an extension to MCNP and both are widely used in the nuclear engineering and health physics communities. In this study, the personal dose equivalent, $H_p(10)$ was calculated in MCNPX by scoring the energy deposition in MeV/g per particle in a thin layer that is behind 10 mm tissue equivalent volume. The geometry in MCNPX is described in figure 2. $H_p(10)$ was calculated for each irradiation event at the operator's neck joint according to the camera tracking file. This location is at 15 cm from the neck joint downward and 7 cm to the left or right side according to the approximate location of the APD in each measurement. The patient was simulated as a BOMAB (BOttle Manikin Absorber) phantom.

2.6.2. PENELOPE/penEasyIR

PENELOPE/penEasyIR is based on PENELOPE v2014 [28] and penEasy [29]. PENELOPE is a standard general-purpose MC code and PenEasy is a general-purpose main program for PENELOPE. In the framework of PODIUM project, penEasy was modified to automate the calculation of personal dose equivalent, and the new program was named penEasyIR. PENELOPE/penEasyIR [31] provides the calculation of personal dose equivalent ($H_p(10)$, $H_p(0.07)$ and $H_p(3)$) from the simulated photon fluence spectrum at a point in air. The geometry used is shown in figure 3. For simplicity, the patient phantom was described by quadric surfaces with a BOMAB Phantom scaled to the patient size. For each irradiation event, the patient was moved according to table movements and the source and the detector were located according to source-to-detector distance and primary/secondary rotations (from the RDSR). For each event, $H_p(10)$ was calculated at several points (points B in figure 3), matching or referring to operator joints from the camera tracking file.

2.6.3. MCGPU-IR

MCGPU-IR is based on MC-GPU [24], a MC simulation code that uses the computational power of graphic processing unit (GPU) cards. The MCGPU-IR code was developed during the PODIUM project and several improvements have been made in comparison to the original MC-GPU. It allows the simulation of a single operator and a shield that attenuates radiation between patient and operator. The code performs two simulations successively, first only with the patient's body irradiated with the original radiation source. Secondly, all the particles that escape from the voxelised geometry of the patient are tested for the intersection with the voxelised phantom of the operator. Those x-rays scattered in the direction of the

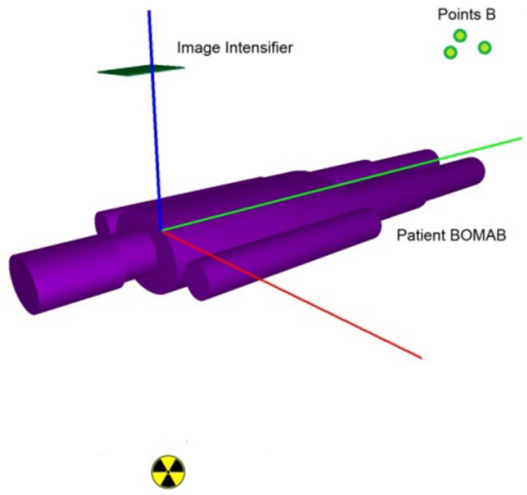

Figure 3. Scheme of geometry used in PENELOPE/penEasyIR simulations.

operator are stored in a phase space file (PSF). Only a small fraction of all the simulated photons are stored in this PSF so those particle histories are reused several times to maximise the deposited dose in operator's voxels as an intrinsic variance reduction technique [24].

3. Results and discussion—measured vs. simulated staff doses

This proof-of-concept in a clinical setting took place from June to October 2019. The strategy was to include a broad range of cases in the feasibility study to allow for a trial of the proof of concept and for refinement of the process in each clinical setting. The data described in section 2 (Materials and methods) was recorded for several clinical procedures. This data was then analysed and prepared; suitable cases were shared with the PODIUM team for simulation. Not all cases were suitable for simulation for various reasons including loss of tracking information, cases with very low doses or very short fluoroscopy times, and cases where the position of the main operator was not visible on the camera. The cases are summarised in table 1. A description of two of these cases (one from each room) is presented in more detail in the following section, along with a review of results from all cases in section 3.3.

3.1. Endovascular room sample case—case E2

3.1.1. Measurement geometry and results for case E2

Measurements took place during an Endovascular Angioplasty with Iliac Stenting procedure. The dose to the main operator (Vascular Surgeon) was measured using an APD worn at their chest pocket over the lead apron (figure 4). The RDSR was anonymised. Motion tracking data was captured with the location of the main operator and matched, based on time stamps, to individual irradiation events from the RDSR. In the RDSR, for several events (13 of the 67) tracking data were not available. In some cases the operator was 'lost' with no skeleton tracking, while other staff in the scene continued to be detected and tracked. The events where the operator was 'lost' comprise around 4 Gy cm^2 or 30% of the total exposure and for these events, the operator position was inferred from his last recorded position.

3.1.2. Monte Carlo simulation geometry and results for case E2

For MCNPX, the cumulative estimated $H_p(10)$ is 34.5 $\pm$ 6 μSv using MCNPX. The simulation time for MCNPX was 120 s per event. For Penelope/penEasyIR code, $H_p(10)$ was calculated for each irradiation event at points known as *SpineShoulder* and *SpineMid* according to the operators position in the camera tracking file. For this case *SpineMid* was closer to the wearing position of APD. Simulation time for Penelope/penEasyIR was also 120 s per event. The cumulative estimated $H_p(10)$ is 32.4 $\pm$ 2 μSv using Penelope/penEasyIR. The simulation time for MCGPU-IR was 59.2 s per event. The cumulative estimated $H_p(10)$ is 35 $\pm$ 4 μSv. The statistical uncertainty for all MC calculations is below 10%. The calculations use the KAP measurement to obtain an absolute dose and the uncertainty quoted includes both the statistical uncertainty and the KAP uncertainty.

Table 1. Summary of measured and simulated cases for feasibility study.

Procedure	Endovascular Case E1 Lower limb angioplasty	Endovascular Case E2 Angioplasty & iliac stenting	Endovascular Case E3 EVAR	Cardiac Case C1 PCI	Cardiac Case C2 Coronary angiography	Cardiac Case C3 PCI
Measurement location	Chest left	Chest left	Chest left	Chest right	Chest right	Chest right
Irradiation events	24	68	144	163	35	110
Patient DAP ($Gy{\cdot}cm^2$)	1.9	14.8	14.5	76	25	33
Ceiling shielding used	**x**	**x**	✓	✓	✓	✓
Shielding simulated	**x**	**x**	✓	✓	✓	✓
Measured $H_p(10)$ (μSv)	5	55	11	31	12	16
MCNPX simulated $H_p(10)$ (μSv)	7 (40%)	34.5 (37%)	36[a] (227%)	109[a] (252%)	16.8[a] (40%)	21>[a] (31%)
(% diff. from measured)			39[b]	655[b]	70.7[b]	88[b]
PenEasyIR simulated $H_p(10)$ (μSv)	—	32.4 (41%)	5.0[a] (55%)	95[a] (206%)	6.0[a] (50%)	3.6[a] (78%)
(% diff. from measured)			10.4[b]	456[b]	107[b]	16.4[b]
MC-GPU-IR Simulated $H_p(10)$ (μSv)	—	35.3 (36%)	—	47[a] (52%)	13[a] (8%)	5[a] (69%)
(% diff. from measured)				245[b]	52[b]	56[b]

[a] Simulated taking ceiling shielding into account.

[b] No account of ceiling shielding, results shown for completeness.

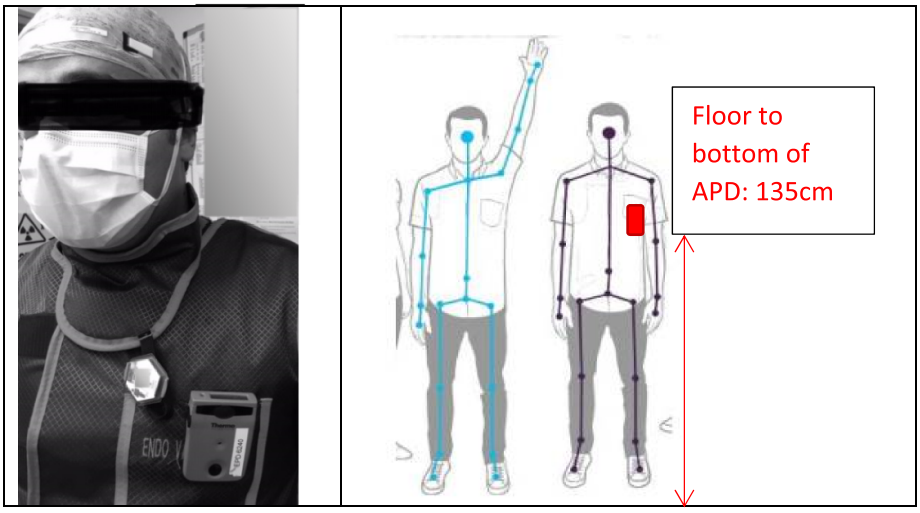

Figure 4. The APD worn by the main operator (left) and the approx. position of the APD used for simulations, taking into account the operators height (right).

3.1.3. Discussion of the results for case E2

The results of the measured dose compared to the simulated dose for this case are promising, with good agreement of 36%–41%. The ceiling shielding was not used in this case, therefore it did not require simulation. Nonetheless there are other limitations and much was learned about the amount of detail required during tracking with these first validation cases. Tracking of the C-arm position relative to the main operator is an issue however C-arm movement was very limited in this particular case. On some occasions as

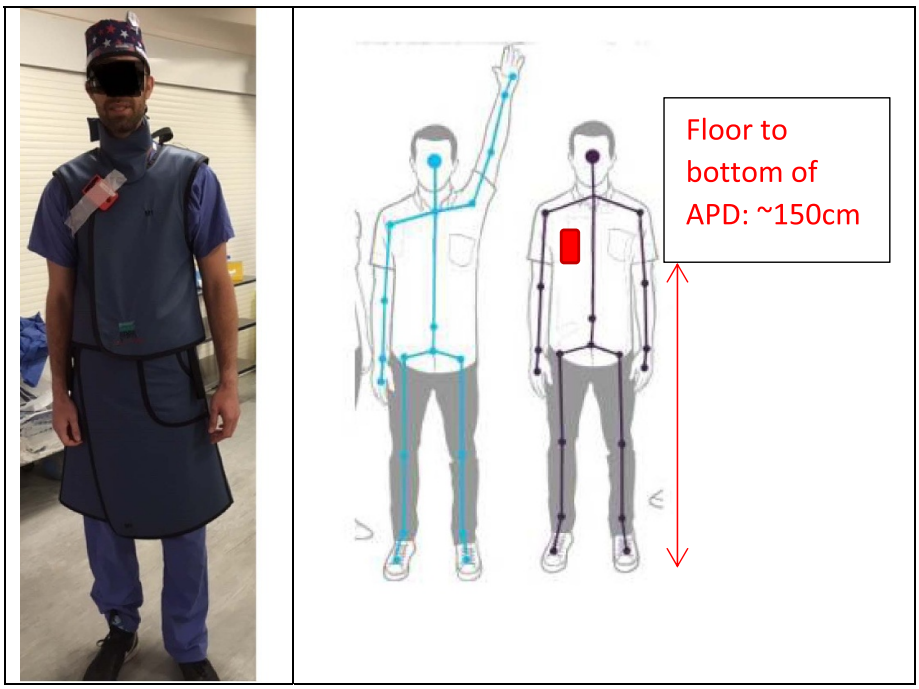

Figure 5. The APD worn by the main operator, and the approx. position of the APD used for simulations, taking into account the operators height.

staff move around the table, skeleton tracking may lose track of the main operator and other staff members may be tracked instead. The observer noted the time periods when this loss of tracking occurred.

3.2. Cardiology room sample case—case C1

3.2.1. Measurement geometry and results for case C1

Measurements were performed on an Interventional Cardiologist during a PCI procedure. An APD was worn over the lead apron at the chest of the main operator, positioned slightly on his right, as there is no pocket on this lead apron to easily attach a dosimeter to figure 5.

The ceiling mounted lead protection (0.5 mm Pb equivalence) was always positioned in front of the main operator during this case however the exact position is not yet easily tracked therefore the position was approximated. Motion tracking data in the Excel files was automatically filtered using a Python script and transformed to compile a single composite file of body IDs related to the main operator only, and related to the timestamp of each irradiation event.

3.2.2. Monte Carlo simulation geometry and results for case C1

For MCNPx, the dose was simulated with 2.4 min simulation time per irradiation and a statistical uncertainty of 5% ($k = 2$). The simulated accumulated dose including the shielding is 109 ± 11 μSv at the dosimeter location. For Penelope/penEasyIR, $H_p(10)$ was calculated for each irradiation event at operator's *Shoulder Right* which is the closest to the actual wearing position of the APD. The RDSR irradiation events were simulated using PENELOPE/penEasyIR code with 2 min simulation time per irradiation and a statistical uncertainty lower than 1%. The simulated accumulated dose, taking into account the shielding is 95 ± 9 μSv at the right shoulder (with $k = 2$). Irradiation events were simulated using MCGPU-IR code with 25 s simulation time per irradiation event, and about 1 h for the whole procedure. The statistical uncertainty is 1.8% ($k = 2$). The simulated accumulated dose including the shielding is 47 ± 5 μSv ($k = 2$). As stated previously, the statistical uncertainty for all MC calculations is below 10%.

3.2.3. Discussion of the results for case C1

One of the major limitations to validate these calculations is that the ceiling mounted shield was used for the entire case however its precise position cannot yet be tracked by the IPS. However, based on observations during the procedure, the shielding was introduced in the MC simulation geometry at a fixed location for the complete procedure and an approximate position and orientation was assumed. Simulations of $H_p(10)$ with and without the ceiling mounted shield show that the shielding would have attenuated 85%–90%, which is in good agreement with published factors for these type of ceiling mounted screens [3, 6]. The differences

between the MC codes are higher than in other cases but acceptable considering the simplifications considered.

3.3. Summary of findings from proof-of-concept in the clinical setting

Measurements were completed during several patient interventional procedures. Three MC codes were used to simulate occupational dose and compare it to dose measured with a physical dosimeter. The results obtained were promising, with differences between simulated staff radiation doses, in terms of the personal dose equivalent quantity $H_p(10)$ of the order of 40%. However in longer and more complex cases including ceiling-mounted radiation shields, this increased to over 200%. This difference can be seen across the range of results presented from all six cases (E1 to C3). Case E1 was a short uncomplicated case with a relatively low patient DAP and low staff dose. The ceiling shield was not used (similarly to Case E2) therefore the shield did not have to be simulated. Case E3 was an EVAR procedure, which is commonly performed; therefore it was useful and more complex to simulate this clinical situation which had many events in the RDSR. The ceiling shield was used in E3 which is good practice from a radiation protection perspective, however this added to the complexity of simulation. Cardiac case C2 and C3 were both carried out by the same doctor (a different doctor to cardiac C1) and the ceiling shield was used consistently by both operators for all three cases. It is also interesting to note that the number of RDSR events is greater for the cases requiring intervention (PCI) and there were more events to simulate for C1 and C3 (both PCI) than for a diagnostic coronary angiogram (C2).

A significant amount of learning took place during all validation cases from being present in the room. While observing the workflow and managing the tracking equipment it was possible to understand what arrangements worked well for different clinical rooms and for clinical procedures. Similar issues were found across all cases and these are discussed further in the Limitations. Tracking of the C-arm position relative to the main operator remains an issue to be solved as the movement of the C-arm is not automatically included in the RDSR. The location of the camera on the TV monitor is a compromise and adds another variable to the validation measurements. The calibration procedure was followed in order to provide data when the monitor was moved. The absence of skeleton tracking data for some irradiation events is noted. Procedures are performed in a teaching hospital and the role of main operator varies during the procedure. The doctors may swap places many times. At these times, the skeleton tracking may lose track of the main operator and other staff members may be tracked instead and careful observations were needed at these times.

Simulation of the ceiling-mounted lead shielding was only possible based on observations and photos. Data on the exact model, dimensions and lead equivalence were used from the manufacturer. For all three MC codes, an object representing the ceiling shield was added into MC code as a volume. This was done similarly in terms of geometry and material for all three codes, with minor adjustments made depending on the phantom or specific aspects of the MC code.

4. Discussion of the clinical requirements and feasibility of real-time dose simulations in a hospital setting

One of the PODIUM project aims was to assess the suitability of the system for a complex interventional hospital setting and to identify the future needs of the system. This was a key focus of the clinical research team prior to, and during the evaluation period, and the following observations were made.

4.1. Evaluating the clinical requirements and feasibility of real-time dose simulations

Our study and a similar series of measurements in Sweden [26] have shown that it is feasible to simulate doses and the PODIUM concept has merit. Many technical challenges were solved and while there were some promising results, the study revealed difficulties and further challenges to be surmounted. A complete real-time system is likely to be several years away from use. In terms of hospital usability, the concept of calculating dose without wearing dosimeters is generally welcomed. Some concerns with a PODIUM-type approach arise around the issue of privacy due to the presence of a camera within a clinical room. This must be carefully considered for the future, and include consultation with legal, ethical, data protection and IT experts in the area to develop a solution that will be acceptable. The safety of the installed equipment in the clinical environment is paramount.

For the validation measurements, equipment had to be installed in the clinical environment and researchers had to be present before/during and after patient treatments. Throughout the PODIUM project we aimed to foster strong collaboration with the clinical team in order to have a successful outcome. Patient and staff consent was required as part of the Research Ethics approval. Although depth-map settings on the camera were used (where no persons are identifiable, as shown in figure 6) it was crucial that there was transparency and consent for this aspect of the project.

Figure 6. Example Kinect™ depth map image.

Some limitations of the current system were identified. A significant number of detailed tasks had to be completed before and during tracking of each validation case, which was not always possible. Improvements could be made using a permanently installed camera in a fixed location with a PC controlling the system outside the x-ray room. The need to record many observations such as the main operator body ID and the movement of the C-arm are time consuming and required a human observer for the validation, and required significant time on analysis after the case. It is possible that for future x-ray systems, the movement of the C-arm will be automatically available and included in the RDSR.

The problem of tracking the main operator body ID was greatly improved with the use of a Python script. It was developed to identify the body ID of the main operator based on an iterative algorithm that compared the position of the different skeletons across multiple frames and this automation solved the need for manual processing.

The results for some cases showed a significant difference across the three MC simulation packages. This has been observed similarly in the Swedish study [26] and possible reasons for this have been considered. One difference is a variation in the exact positioning of the field on the patient phantom, and the composition of the phantom that it used by the MC code. In terms of the operator phantom and the calculation of $H_p(10)$, in PENELOPE/penEASy the operator phantom scores fluence free-in-air. For MCNPx the operator is a slab phantom, and MCGPU-IR uses an anthropomorphic phantom for the operator. Differences may also occur due to simulation of the ceiling shield. For all three MC codes, an object representing the ceiling shield was added into MC code as a volume. It was done similarly in terms of geometry and the lead equivalence, however minor adjustments may have been required depending on the patient and table position and how it intersects with the ceiling screen in the simulation code. In order to achieve better consistency in results across different codes, it would be important to know the exact location of the field on the patient and the exact location of the ceiling-shield and these are areas for future work.

There are also scenarios where the physical measuring device (APD) might underestimate exposure for example the operator may shield the dosemeter on their trunk with their arms during a procedure [26]. Another limitation of the PODIUM system is that it will only be compatible with modern systems capable of producing an RDSR. Older systems without an RDSR will not be compatible. This is likely to become less of a problem in future years with dose management systems becoming more and more integral parts of hospital radiology IT systems. However, it should be borne in mind that at this time, quick and easy access to an RDSR at the push of a button may not be an option for many users of interventional systems.

If only one camera is used, with several staff members moving around the room, occlusion is clearly an important issue, and may lead to an incorrect skeleton representation of the operator. In some cases where two operators were very closely working together the system can overlap as shown in figure 7 and this separation of staff members needs to be improved. In addition, for clinical reasons and patient access, in

Figure 7. Example of skeleton tracking overlapping (two operators but only one skeleton identified).

some cases staff will stand on the opposite side of the table to that where the camera is pointed. For these cases they are untracked and totally out of the field of view. For these reasons, work had commenced towards the latter part of the project on a multi-camera solution.

The problem of occlusion can not only result in incorrect skeletal representation but the camera can also swap the Body ID between two staff members if they pass by close to each other or swap positions. Changes can also occur during digital acquisition runs, as it is good radiation protection practice for staff to step back from the table as far as possible during these runs which generate relatively high levels of scattered radiation. If they step back, staff may leave the field of view of the camera and be assigned a new body ID when they return and the IPS must be able to account for this. Work will need to continue on a system to ensure that the IPS recognises the person that was being tracked and a two-camera system can resolve this issue.

Consideration should be given to who, in the hospital setting, will install and manage the equipment for a PODIUM solution. The equipment used is generally not considered electro-medical equipment as it is not intended for treatment on patients, yet it will be close to or within the patient environment. This type of installation will require close collaboration between hospital medical physicists/clinical engineers, radiation safety advisers, radiographers, clinical teams and IT support staff. At an absolute minimum, all equipment must be CE marked. Vendors of x-ray equipment and personal radiation dosimeters should be closely involved in developing future solutions due to their expertise in meeting strict equipment standards. Input from IT experts working in a healthcare is also needed in terms of security, access to third party hardware and software. IT requirements are crucial to the smooth installation and functioning of a computer simulated approach to personal dosimetry. The duration of these procedures typically varies from about 15 min to 2 h, but could be up to 10 h for some highly complex fenestrated EVAR (FEVAR) cases. This will create very large tracking files. Typical file sizes should be determined and minimised where possible. This issue could be solved by only storing data when the beam is on, using file compression or using different file formats.

4.2. Recommendations for future improvements

We have shown that in terms of overall hospital usability, the preliminary results from PODIUM are promising however further improvements are needed to progress towards a complete occupational dosimetry solution. Staff radiation doses were calculated by combining positioning information from individual staff members using the IPS based on the Microsoft Kinect™ 3D camera, combined with information on the radiation source. We have also considered in the previous section some of the limitations that may lead to differences between calculations and measurements. The list of recommendations below is intended to provide some guidance on future needs and areas where limitations may be reduced or eliminated.

- A PODIUM-type solution should be designed to be integrated, discrete and wireless with fast performance. It should be easy to mount in an x-ray room and safe for a clinical environment.

- Tracking of the main operator in a reliable and fully automated way, taking into account the real clinical situation (occlusions, staff swapping roles, staff leaving the room) is a key challenge to be addressed.
- Automated tracking of the ceiling-lead screen and the x-ray C-arm must also be solved.
- The minimum technical requirements for the x-ray system must be established i.e. an RDSR file in the DICOM standard is a prerequisite, along with any key exposure parameters that are mandatory in the RDSR for PODIUM.
- Work should continue with x-ray vendors to have more real-time dose information and C-arm positional information.
- The minimum technical requirements for the IT solution must be established, along with details on expected file size and storage requirements.
- A detailed user manual for installation and operation, and a training programme should be developed.
- Privacy, ethics, data protection and security aspects must be clearly established for example in relation to GDPR and relevant national requirements. Care must be taken to keep all those present in the room fully informed of any camera tracking and privacy/anonymity maintained wherever possible.
- The time to manage the system should not exceed current time requirements for managing individual personal dosimetry programmes.
- Work done by the project partners on the legal aspects of seeking approval for PODIUM to be an approved dosimetry service should continue.
- Further validation in clinical settings is needed.

5. Conclusions and future work

We have shown here the feasibility of a real-time occupational dose application for clinical use in an Endovascular and Interventional Cardiology setting. A new method was assessed, during live cases in the complex clinical setting and the equipment and software was able to track staff and produce dose estimates. The dose to the main operator was measured using an APD worn over the lead apron and compared with the dose simulated using three MC codes. The first results from the validation show promise however, on detailed analysis some showed difficulties when comparing measured and simulated values in complex situations. Differences were also observed across the three MC codes. Work on improving the PODIUM system for such complex cases continues. The experience gained from the measurements in a clinical setting has informed the list of recommendations above on future needs. These issues are seen as key factors that must be addressed for the future success of a tool such as PODIUM. PODIUM is perceived as a novel way forward and interventional staff are interested in the possibility of instant dosimetry results, and of the convenience of dosimetry without individual dosimeters. 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 Interventional radiology/cardiology environment is one of the most complex situations for personal dosimetry so it was ambitious yet highly worthwhile to try the early proof-of-concept PODIUM approach in this field and it may prove easier to implement in other workplaces. The PODIUM project was completed successfully over a two year period from January 2018 to December 2019 [16]. The Technology Readiness Level (TRL) for PODIUM is currently categorised as TRL 5 (technology validated in relevant environment) [32]. This work has shown the use of a new system in a clinical environment and how many of the technical problems were overcome. Several more years of development will be required to complete a second phase with the aim of achieving TRL of 8 or 9 (system complete and proven in operational environment). Future work includes testing of the complete online tool with further measurements in a clinical setting moving forward from the proof-of-concept stage. It is clear that there is great promise in continuing to develop this type of solution for calculating dose without the need to wear an individual dosimeter.

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