Radiation Protection Dosimetry (2020), Vol. 188, No. 1, pp. 22–29
Advance Access publication 12 December 2019
doi:10.1093/rpd/ncz253

THE USE OF ACTIVE PERSONAL DOSEMETERS IN INTERVENTIONAL WORKPLACES IN HOSPITALS: COMPARISON BETWEEN ACTIVE AND PASSIVE DOSEMETERS WORN SIMULTANEOUSLY BY MEDICAL STAFF

F. Vanhavere[1,*], E. Carinou[2], I. Clairand[3], O. Ciraj-Bjelac[4], F. De Monte[5], J. Domienik-Andrzejewska[6], P. Ferrari[7], M. Ginjaume[8], Hrvoje Hršak[9], O. Hupe[10], Z. Knezevic[11], U. O'Connor[12], M. Sans Merce[13], S. Sarmento[14], A. Savary[3] and T. Siskoonen[15]
[1]SCK-CEN, Belgian Nuclear Research Centre, Mol, Belgium
[2]Greek Atomic Energy Commission, EEAE, Agia Paraskevi, Attiki, Greece
[3]IRSN, Institute for Radiological Protection and Nuclear Safery, Fontenay-Aux-Roses, France
[4]Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[5]Veneto Institute of Oncology IOV—IRCCS, Padua, Italy
[6]NIOM, Nofer Institute of Occupational Medicine, Lodz, Poland
[7]ENEA. IRP—Radiation Protection Institute, Bologna, Italy
[8]UPC, Universitat Politècnica de Catalunya, Barcelona, Spain
[9]University Hospital Centre Zagreb, Croatia
[10]Physikalisch-Technische Bundesanstalt (PTB), 38116 Braunschweig, Germany
[11]Ruder Boskovic Institute RBI, Zagreb, Croatia
[12]St. James's Hospital, Dublin 8, Ireland
[13]CHUV, Centre Hospitalier Universitaire Vaudois, Lausanne, Switzerland
[14]Porto Research Center (CI-IPOP), Portuguese Oncology Institute of Porto (IPO Porto), Porto, Portugal
[15]STUK, Helsinki, Finland

*Corresponding authorfvanhave@sckcen.be

Received 11 May 2019; revised 11 May 2019; editorial decision 12 July 2019; accepted 12 July 2019

Medical staff in interventional procedures are among the professionals with the highest occupational doses. Active personal dosemeters (APDs) can help in optimizing the exposure during interventional procedures. However, there can be problems when using APDs during interventional procedures, due to the specific energy and angular distribution of the radiation field and because of the pulsed nature of the radiation. Many parameters like the type of interventional procedure, personal habits and working techniques, protection tools used and X-ray field characteristics influence the occupational exposure and the scattered radiation around the patient. In this paper, we compare the results from three types of APDs with a passive personal dosimetry system while being used in real clinical environment by the interventional staff. The results show that there is a large spread in the ratios of the passive and active devices.

INTRODUCTION

The European radiation dosimetry (EURADOS) group comprises a self-sustainable network of more than 70 European institutions, such as research centers, university institutes, reference laboratories, dosimetry services and companies. The core of EURADOS activities is aimed at promoting scientific and technical research and development in the field of ionizing radiation dosimetry. Much of the work is performed in working groups (WGs), of which eight are active at the moment in different dosimetry-related topics. WG 12 (WG12) is dealing with various aspects of dosimetry in medical imaging, including occupational and patient exposure. In the framework of studying the doses of exposed workers in medical facilities, one of the activities of WG12 in recent years has been focused on the use of active personal dosemeters (APDs) in hospitals, and this paper will report on this issue.

APDs are mainly used as a tool in new techniques or as alarm dosemeters in potential high dose areas and help in the application of the optimization of protection [(1)]. Nevertheless, passive dosimetry systems are still the primary choice used to evaluate occupational exposure to ionizing radiation and to verify compliance with dose limits imposed by the national regulations. Considering that occupational exposure in medicine is a matter of growing concern, the use of APDs is expanded in various fields of practices of ionizing radiation in medicine.

It is not the first time that an EURADOS WG looks into the use of APDs in hospitals. Already

in 2001, the EURADOS WG2 (harmonization of individual monitoring) focussed on new developments in individual monitoring with an emphasis on the possibilities and performances of different active dosemeters. One of the actions performed was a questionnaire to the users of APDs in industry and hospitals [2,3]. It was shown that at that time APDs were rarely used in hospitals. An intercomparison of APDs for the monitoring of external exposure from photon and beta radiation was organized as a joint venture project of EURADOS and International Atomic Energy Agency to assess the technical capabilities of different types of APDs. It was concluded that the general dosimetric performance of the tested APDs was comparable with the performance of standard passive dosimetric systems [4]. A decade later the Optimization of RAdiation protection of MEDical staff (ORAMED) project focussed on the use of APDs in hospitals. Different existing APDs were tested in both laboratory conditions and conditions that are met in clinical practice (e.g. pulsed fields and low energies) and a series of guidelines for the use of these APDs in interventional cardiology (IC) and interventional radiology (IR) workplaces were prepared [5–7]. Most APDs had satisfactory energy and angular responses. However, in pulsed radiation fields, the response of most APDs decreases when the instantaneous personal dose equivalent rate increases [8].

Almost a decade passed since the beginning of the ORAMED project, and over the years, a number of new facts and developments have become available, including new types of dosemeters, standardization of tests for pulsed radiation fields [9,10] and evident increase in the use of APDs in hospitals. In addition to the development in the dosimetry field, the applications of ionizing radiation in medicine become technologically advanced and more complex and diverse. Therefore, it was decided to perform a new study under the auspices of EURADOS WG12. Within this framework, the following actions have been defined:

- to perform an extensive survey to collect all relevant information and identify issues related to the use of APDs in medical applications of ionizing radiation. This part of the work is finished and the results have been published [11];
- to test the influence of lead aprons on the calibration and use of APDs and passive dosemeters. Also, this part has been recently published [12];
- to perform a series of tests of APDs in standard continuous and pulsed fields. The most used APDs—as indicated by the survey—were tested in standard RQR fields and in pulsed fields according to the new ISO technical specification [13];
- to perform tests in hospitals with an objective to assess the performance of APDs in the clinical environment. This action consists of two parts. On the one hand, the response of some APDs was compared to reference measurements in realistic hospital fields for several fixed set-ups using interventional equipment. On the other hand, some selected APDs were worn together with a passive dosemeter by medical staff in several European hospitals in various interventional practices.

The goal of all the actions listed above is to come with updated recommendations on the use of APDs in hospitals, which will be completed, once all tests have been finalized.

This paper will report only about the part of the hospital tests, where APDs are compared with a reference passive dosemeter. The main objective of these tests was to have an overview of differences between active and passive dosimetry in routine practice in hospitals, where all kinds of procedures and parameter settings are used without an accurate knowledge of the field parameters. Similar tests were performed about 10 years ago within the ORAMED project [6].

The tests in the hospitals during the ORAMED project were not conclusive. There was a large spread in the results when comparing different APDs with passive dosemeters worn together by medical staff. There were both under and over responses with respect to the considered reference value and no clear link was found with the characteristics of the type of APD to explain the differences that were found. There could be several reasons why these tests were inconclusive, but one major limitation was that no record was held on how the dosemeters were positioned. The APD could have been worn on a completely different position on the body of the medical worker compared to the passive dosemeter. And since the scatter radiation field in IR and IC is extremely inhomogeneous over the body of the worker, this could have a major impact on the results.

Therefore, it was decided to repeat this comparison exercise, with the following improvements:

- both the APD and the passive dosemeter were put in a fixed holder so that their relative position was always the same for each worker in each hospital without shadowing one another;
- bigger sample of data was collected (for an APD of a given type) by restricting to only three types of APDs and by involving more participating hospitals;
- guidelines on how to wear the dosemeters were written and distributed;
- more information was collected on the procedures that were performed by the staff during the monitoring period.

The aim of the part of the study described in the present paper is to test the reliability of APDs for

Figure 1. Picture of the holder for the EPD Mk2.3 that is fixed to the RPL passive dosemeter.

medical staff monitoring in interventional practices by comparing their response with one specific type of passive dosemeters, assumed as reference. The results will be useful to outline future recommendations on the use of APDs in hospitals for personnel dosimetry.

MATERIALS AND METHODS

For the comparison campaign, the operators wore, side by side, one APD and one passive dosemeter above the lead apron. The two dosemeters were tied together in a holder like the one in Figure 1. This means that the relative position was always the same. The holder will not shield the dosemeters from the scattered radiation from the patient, nor will the APD shield the passive dosemeter. The angle between the incident radiation and the detector for both dosemeters is basically the same.

In order to improve the uncertainty assessment, it was decided to register the dosemeter values that have reached, at least, 300 μSv. To obtain such doses, the dosemeters needed to be worn for many procedures by the same operator. The exercise was performed in 11 countries from institutes participating in EURADOS WG12, so that enough data points could be collected. Each institute was responsible for distributing the holders with the active and passive dosemeters in selected hospitals in their country. After receiving the required dose, the dosemeters were collected, and the doses from the APDs were noted down. In Table 2, the number of measurement points collected in each country is shown.

As passive dosemeter, one single type of dosemeter was chosen for all measurements performed within the campaign. The routine personal dosemeter that is distributed by IRSN in France was selected. This dosemeter is based on radiophotoluminescence (RPL); it contains a silver activated phosphate glass. If the glassis irradiated with ionizing radiations luminescence is emitted when exposed to UV light, the amount of luminescence is directly proportitional to the dose. This system is approved by the French accreditation committee. All passive dosemeters were collected and resent to IRSN after the measurements. They were processed according to normal routine measurement procedures.

Three types of active dosemeters were selected: EPD Mk2.3, DMC 3000 and RaySafe i2 (Table 1).

This choice was based on the results from the questionnaire; these APDs are among the most used in different European hospitals [11]. A second criteria was the availability of detailed test results in standard fields to be able to compare the results with lab experiments.

To ensure that results in the different countries were comparable, a common protocol was developed. The dosemeters were worn during several interventions to integrate doses to at least 300 μSv for several types of IR and IC procedures. They were worn above the lead apron, at a location close to the routine position. The alarm of the APD was always switched off in order not to interfere with the medical practice. The dosemeters were worn by the primary operators in interventional procedure room/theatres. If possible, it was advised to record the type of procedures, the

Table 1. Manufacturers and models of APDs with their basic properties.

Manufacturer	Type	Type of detector	X and gamma energy range	Dose/dose rate range	Accuracy
Mirion Technologies	DMC 3000	Silicon diode	15 keV to 7 MeV	1 μSv to 10 Sv 0.1 μSv/h to 10 Sv/h	≤ ± 10%
Thermo Fisher Scientific	EPD MK2.3	Silicon diode	15 keV to 7 MeV	0 μSv to 16 Sv 0 μSv/h to 4 Sv/h	≤ ± 10%
RaySafe	i2	Silicon diode	33 keV to 101 keV	1 μSv to 10 Sv	5%

number of procedures and the protection measures used, but this was not systematically possible. Still, the results are useful, as they will represent a snapshot of the real situation in a hospital, where different types of procedures are used with varying degrees of radiation protection tools. The goal was to have 3–4 different operators monitored, for 3 periods with the same person.

The background of the RPLs was measured by control RPL dosemeters, that accompanied the measurements during the campaign. This background subtraction was important because it could take several months before the data were collected, and the RPL dosemeters were returned to IRSN and readout. The background radiation from the APD, on the other hand, was not taken into account, because there were in most cases maximum 2 weeks between the start of the measurement and the noting down of the results, resulting in a maximum of about 28 μSv. This would not change any conclusions.

The dose equivalent was provided by the passive dosemeter according to the routine measurement protocol of the RPL dosemeter by IRSN. Both $H_p(10)$ and $H_p(0.07)$ were evaluated by the RPL dosemeter and also by the EPD Mk2.3 and DMC 3000 dosemeter. The RaySafe i2 only gives $H_p(10)$ measurements. It was decided to focus only on the $H_p(10)$ results, as these are the most relevant. The results did not differ markedly for $H_p(0.07)$.

It was decided that no systematic individual calibration of each APD was to be done as the dosemeters have a type approval, and from experience it could be expected that the calibration is within an acceptable range. This have been proven by some checks of the calibration, all within 5% as expected. The uncertainty from this is expected to be negligeable (less than 5%) compared to the overall spread in results. For the RaySafe i2 devices, however, the individual spread is larger from one device to another. For the measurements performed in one country (Portugal), an individual calibration was applied for the RaySafe i2 devices.

RESULTS

Although the protocol indicated that at least 300 μSv is needed to be integrated as dose on the APD, some data with lower values were reported. It was decided to include into the analysis all data points where both the RPL or APD values were higher than 100 μSv. The resulting valid points are listed in Table 2.

For each data point, the ratio APD/RPL was calculated, per country and per type of APD; the averages and the respective standard deviations were calculated as well. The results are shown in Table 2.

The values for all three types of dosemeters are similarly distributed, as can be seen in Figure 2.

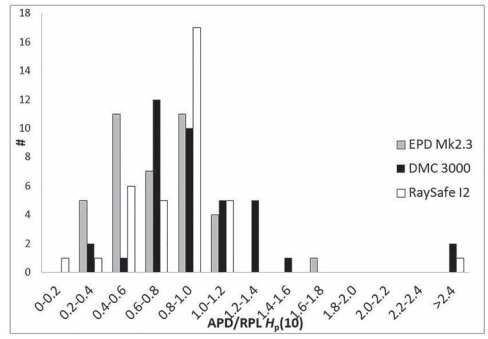

Figure 2. Histogram of the ratios APD/RPLfor the different types of active dosemeters.

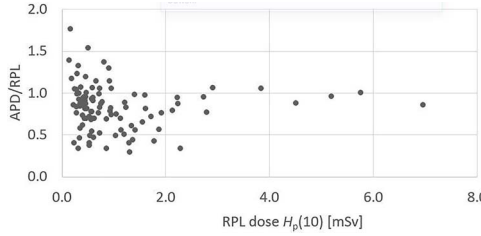

Figure 3. Ratios of the APD/RPL for all devices as a function of the RPL indicated dose.

When the ratios of the dose results are plotted againt the recorded dose for each type of APD, graphs, as shown in Figure 3, are obtained. As expected, the ratio has a larger spread for lower doses and approaches more to 1 for higher values.

In Table 2 it can be seen that the values from the RaySafe i2 in Portugal are deviating from the others. These results were investigated in detail, and we contacted the hospital and operators again to find out if something went wrong during the measurements. The procedures were standard interventional radiology procedures (nephrostomies, gastrostomies, biliary drainages, TACE, etc.), and no explanation was found for the differences. The three RaySafe i2 devices were afterwards individually calibrated, and correction factors between 0.8 and 1.2 were applied to the results of the three devices. However, this did not change the significant deviation found in the ratios with the passive devices. As it was not possible to repeat the measurements in this hospital, it was decided to remove these data from the further analyses.

DISCUSSION

As can be seen in Table 2, the typical spread in results is about 40–50%. During the ORAMED project [6] the spread was even higher. Due to the fixed position of the RPL compared to the APD, more coherent

Table 2. Ratio of APD/RPL (data points per country and per type of APD used in the campaign).

EPD Mk2.3						
Country	# data	Avg APD/RPL	St dev %	Median	Min	Max
Greece	11	0.59	38	0.55	0.34	1.06
Belgium	10	0.65	30	0.64	0.40	0.98
Poland	10	0.80	44	0.81	0.29	1.76
Ireland	8	0.93	16	0.95	0.70	1.14
Total	**39**	**0.73**	**41**	**0.70**	**0.29**	**1.76**
DMC 3000						
Switz.	15	0.99	25	0.94	0.68	1.39
Serbia	5	1.28	79	0.94	0.40	2.92
Italy	12	0.78	24	0.84	0.34	1.05
Croatia	6	1.25	67	0.94	0.69	2.89
Total	**38**	**1.00**	**52**	**0.88**	**0.34**	**2.92**
RaySafe i2						
Portugal	7	0.44	49	0.46	0.16	0.80
Spain	17	0.92	11	0.89	0.76	1.14
Italy	6	0.83	11	0.84	0.68	0.96
Finland	6	1.13	89	0.77	0.47	3.10
Total	36	0.84	54	0.84	0.16	3.10
Total without Portugal	**29**	**0.94**	**47**	**0.87**	**0.47**	**3.10**

results are now obtained in this study. Still, this 40–50% is quite large, and there must be reasons for these differences.

In the ORAMED project, about 100 measurements were collected for five devices. Except for the DMC 2000XB (where about 40 measurements were collected), the statistics are much better now, with more than 35 data points per APD.

Two of the APDs used in the ORAMED project were the same as in this campaign. For the EPD Mk2.3, a median APD/RPL ratio was found of 0.77 in ORAMED, compared to 0.70 from this study. So this is comparable. For the RaySafe i2, in the ORAMED project, the average ratio was 0.61, compared to 0.87 this time. But for the ORAMED campaign, only five data points were collected, so it is difficult to make any comparison.

For the DMC, an earlier version was used, the DMC 2000XB, compared to the EPD Mk2.3 and the DMC 3000 used in this work. The energy dependence of the DMC 2000 was presented at the IRPA confernce [14]. The DMC 3000 has a better response for pulsed radiation [15] compared to the DMC 2000 XB version, so this could have an effect. In the ORAMED project, the average ratio found was 0.77, while this time we found 0.88. Both experiments have enough data points, and the results seem to show a better response for the newer version. But of course, the standard deviation of both experiments (50% now compared to 70% in ORAMED) is too large to see any difference possibly caused by an improved response to pulsed radiation.

It must be stressed that also the passive dosemeter was different in both exercises. In the ORAMED project, different types of passive dosemeters were used, while now the same RPL dosemeter was used for all experiments. Although in general, passive dosemeters behave well in intercomparisons and give results within the trumpet curve, differences up to 20% can be found for some energies. Typically, TLDs give a slight overestimation for lower X-ray energies as encountered in hospitals, while the RPL has a more flat response.

The integrated doses ‘should be high enough so that statistical effects are negligeable. The IEC tests [16] have as criteria for the coefficient of variation at 100 μSv to be less than 15%. Common APDs are sensitive enough so that their variation in repeatability is less than 5% when doses are above 100 μSv [4,8]. The coefficient of variation at 100 μSv for RPL is 5%. This means the uncertainty coming from statistics on the ratio of the APD and RPL is smaller than 7%. This is much smaller than the spread found in Table 2. It can be seen in Figure 3 that the lower the dose, the higher is the spread. But even for values of around 1 mSv, the ratios are between 0.5 and 1.5, which is markedly higher than what could be expected just from statistics. So the statistical variance is not the main cause of the spread and differences, and other effects play a role.

The three different types of APDs also show some differences in results. The EPD Mk2.3 shows clearly lower results compared to the RPL than the other two, with the exception of the Irish results (see

Table 3. Energy responses of the APDs and the RPL.

Response relative to $H_p(10)$	EPD Mk2.3	DMC 3000	RaySafe i2	RPL
RQR5	1.0	1.2	0.9	-
RQR9	1.0	1.1	1.1	-
N-30–N-120 min and max	0.8–1.2	0.9–1.3	0.4–1.1	0.9–1.1
Average N-30–N-120	1.0	1.1	0.9	1.0

Table 4. Response for standardized pulsed fields.

	Response relative to continuous field RQR8		
Dose rates of the pulsed fields (Sv/h)	EPD Mk2.3	DMC 3000	RaySafe i2
1	0.9	1.0	0.5
5	0.5	0.7	0.2
10	0.3	0.6	0.1

further). The energy and angular dependences of RPL and APD are examined in order to see if these can explain some of the differences met in the study.

The dosemeters are worn in a random variety of standard procedures. So the exact energy spectrum encountered is not known, except that it lies within the values of 20–120 keV for interventional procedures and it is mainly radiation scattered by the patient. The RPL energy response was measured during the type testing. Between 20 and 120 keV, the response is within 10% of the reference value. The response of the 3 types of APDs is summarized in Table 3. The data for the RQR-series are measured within the WG12 activities [15], while also the results for the whole N-series were measured during the ORAMED tests.

These results show that the energy response difference cannot explain the results found in the hospital tests. From these results, we can expect slightly higher values for the DMC 3000, while from the measurement campaign we found similar or even slightly lower values. For the RaySafe i2 dosemeter we expect lower values, which are confirmed by the results in the campaign. The EPD Mk2.3 has similar energy characteristics to the RPL, while the hospital results show lower values. So the energy characteristics alone cannot explain the results.

In the hospital workplaces, there is also a variety of realistic angles where the different dosemeters can be placed due to the movement of the operators. Some angular testing results are available in the ORAMED report and also from the RPL type testing. The RPL dosemeters show a slight decrease in $H_p(10)$ response of about 10% for 60° and the N-40 and N-60 radiation qualities, compared to 0°. For the EPD Mk2.3 and the DMC 2000XB, the relative $H_p(10)$ response was also within 20% for 60° and the N-40 and N-60 radiation qualities, giving a slight overresponse. So when comparing the response of APDs to the RPLs, we expect to find overestimations by the APDs, because their relative response to $H_p(10)$ is increased for higher angles, while the one for the RPL decreases. And this is the inverse of what we see in Table 2.

Table 5. Response for hospital fields.

		Response relative to reference $H_p(10)$		
	Dose rate in pulsed beam (Sv/h)	EPD Mk2.3	DMC 3000	RaySafe i2
Scattered field/tube below	0.2	0.9	1.1	0.7
Scattered field/tube above	0.4	0.8	1.1	0.6
Direct beam	74	0.1	0.2	0

However, other data [17] show that at even higher angles (80°), the response of these both types of APDs is decreasing fast. Such high angles are possible in IR/IC procedures, because the operator is primarily exposed to the radiation scattered by the patient. For the RPL, no data at 80° are available, as this is not required for the type testing. For the RaySafe i2, no consistent angular dependency data could be found. Because the direction of exposure is far from constant during the procedure and hence not known and because of the lack of reference data for the dosemeters, it is difficult to draw any conclusions on the influence of the angular responses. In general, however, we can conclude that the angular responses alone cannot explain the results from Table 2.

Another factor that could be a cause of differences is the pulsed field response. By definition, the RPL is not influenced by the pulsed nature. In WG12, several tests have been performed in standardized pulsed fields [15]. Some of the results at RQR8 pulsed fields are shown in Table 4 where the relative response at a certain instantaneous dose rate (dose rate in the pulse) relative to the continuous field is presented.

Tests have also been performed in a hospital set-up [15]. Here the response of the three APDs has been tested relative to reference measurements for three standard set-ups: scattered radiation field with tube

Table 6. Typical radiation field characteristics in interventional radiology and cardiology workplaces, with the characteristics of the interventional radiology workplace in Ireland used for the present study.

	Typical interventional radiology and cardiology characteristics (reproduced from Table 3.1 of ORAMED report 2012)	Typical interventional radiology characteristics used during procedures in Ireland for this study
Peak high voltage	60–120 kV	65–90 kVp
X-ray tube current	5–1000 mA	93–250 mA (fluoro)
Inherent Al equivalent filtration	4.5 mm	>2.5 mm
Additional Cu filtration	0.2–0.9 mm	0.2–0.6 mm
Pulse duration	1–20 ms	7 ms
Pulse frequency	7.5–12.5 pps	10 pps
Field size	10–17 cm	42 cm (range: 11–48 cm)

below the table and tube above the table and direct beam. These results can be seen in Table 5.

These results show clearly that the higher the dose rate in the pulse, the lower the response for all devices. The DMC 3000 seems to react better to pulsed fields than the other two dosemeters used in the present study. All cases from where we have collected the results in this campaign have the tube below the table. For these kinds of instantaneous dose rates, there is little effect of the pulsed nature of the radiation. When protection means are used, like ceiling suspended screen, the instanteneous dose rates can even be lower. From Tables 4 and 5, we can see that this is less than 10% for the EPD Mk2.3 and no effect for the DMC 3000. The RaySafe i2 can indeed have a decreased response because of the pulsed fields, by the order of 30%. It cannot be excluded that during the real procedures, the operators approached the patient while the X-rays were on, exposing themselves and the dosemeters in a higher dose rate, and thus causing decreased responses for the dosemeters. Also, exposure of the dosemeters to the direct beam is possible, although most unlikely. So the lower response of the EPD Mk2.3 compared to the DMC 3000 and compared to the RPL could be partially explained by this pulsed effect.

The procedures followed in the hospitals were chosen randomly and not limited to any one interventional setting such as interventional radioloy or IC, which can certainly cause differences from one hospital to another. One example is the result from the measurements in Ireland. The ratio of APD/RPL is significantly higher than the other results with the EPD MK2.3 indicating that the APD in this case responded more closely to the passive RPL dosemeter. For the group of participants issued with the EPD MK2.3, the Ireland measurements were carried out during interventional radiology procedures, while the other three institutes in this group mainly monitored IC procedures. The typical characteristics of both types of procedures are summarized in Table 6.

In Table 6 it can be seen that the settings do not differ markedly from the typical range of settings used across IR and IC settings. The average energy used is a bit lower, while the field size is generally larger in IR. For really low energies, the EPD Mk2.3 response increases by 10–20%, which could cause some difference compared to the higher energy IC results. But in general, these differences are not such that they can explain the difference in response from 0.7 to 0.9. So these results are kept in the analyses, as an indicator of the spread that can be obtained for different procedures.

CONCLUSION

In our experimental campaign, we have equipped operators in IR/IC procedures in hospitals with a set of a passive and an active dosemeter. This was done for three types of APDs, in 11 different countries. More than 110 valid data points were collected, comparing the results of the active and passive devices. By fixing both dosemeters in one single holder, geometry effects shadowing one another were excluded. This reduced the spread compared to earlier campaigns, but still, a large variation of ratios was found. The EPD Mk2.3 had on average a 30% lower response than the reference RPL passive dosemeter. The DMC 3000 and the RaySafe i2 had both around 10% lower response. Standard deviations ranged from 40 to 50% for the three types of active dosemeters.

The dosemeters are worn in a random variety of standard interventional procedures, with a random range of energies, angles and pulse field characteristics. We used different laboratory and hospital tests to know which relative behavior we would expect compared to the RPL. For the EPD Mk2.3 we would expect similar responses based on the lab results; however, we found a 25% lower response. For the DMC 3000 devices, we would expect an over-response with even 20 or 30% compared to the RPL, but here we find with our staff measurements similar response. Only the ratio of EPD Mk2.3 versus DMC 3000 is

similar in both lab experiments and hospital experiments. For the RaySafe i2, the lab results give the same order of magnitude difference than the staff results. Again, we must stress that there is a large spread in results so that it is difficult to make such conclusions. Also lack of angular reference data at higher angles (>60°) makes it difficult to estimate the angular effects.

It is clear that experiments with fixed set-ups in laboratory and hospitals do not reproduce well the results obtained from exposing the dosemeter on medical staff in a variety of interventional settings during routine work in a hospital. One other aspect for consideration is the inhomogeneity of the radiation field. Even though the relative positions of the APD and RPL is fixed, the RPL was always positioned below the APD, thus receiving more radiation. Of course, it depends on where exactly the dosemeter is put on the body of the operator and also on the distance to the patient (as well as on all other procedure parameters like field size, angulation and energy). Some exploratory Monte Carlo simulations showed that the 5 cm difference between the center of the APD and the center of the RPL could lead to even 5–15% of the difference in dose rate. This inhomogeneity of the radiation field over the body of the operator will be a topic for future work, but at least this could also explain partially why the results of the RPL are higher compared to the APD than expected.

From our tests, we can conclude that comparing active and passive dosemeters is not straightforward in routine operations, certainly not in hospital settings, where a range of energies, angles and pulsed field characteristics occur at which dosemeter performances can vary significantly. Also, the relative position on the body of the operator can be a big influence factor. This shows again that the uncertainty in personal dose measurements in routine is high, and a factor of 1.5 in such measurements, as recommended by ICRP 75 [(18)] is not excessive. In our experiments in hospitals, we found that APDs show consistently lower values than passive RPL dosemeters during standard IR/IC procedures, and this should be borne in mind when monitoring staff dose using pulsed radiation sources. It is clear that although APDs are a useful tool in a hospital setting, further work is needed to characterize their response in pulsed fields.

REFERENCES

1. Ginjaume, M. *Performance and approval procedures for active personal dosemeters*. Radiat. Prot. Dosim. **144**(1–4), 144–149 (2011).
2. Bolognese, T., Ginjaume, M., Luszik-Bhadra, M., Vanhavere, F., Wahl, W. and Weeks, A. *Active personal dosemeters (APD) for individual monitoring and other new developments*. Radiat. Prot. Dosim. **112**(1), 141–168 (2004).
3. Ginjaume, M., Bolognese, T., Luszik-Bhadra, M., Vanhavere, F., Wahl, W. and Weeks, A. *Overview of active personal dosemeters for individual monitoring in the European Union*. Radiat. Prot. Dosim. **125**(1–4), 261–266 (2007).
4. International Atomic Energy Agency. *Intercomparison of personal dose equivalent measurements by active personal dosimeters. Final Report of a joint IAEA EURADOS Project*. IAEA Report IAEA-TECDOC-1564 (IAEA, Vienna) (2007).
5. Clairand, I. *et al. Active personal dosemeters in interventional radiology: tests in laboratory conditions and in hospitals*. Radiat. Prot. Dosim. **144**(1–4), 453–458 (2011).
6. Struelens, L. *et al. Use of active personal dosemeters in interventional radiology/cardiology: tests in hospitals*. Radiat. Meas. **46**(11), 1258–1261 (2011).
7. Clairand, I. *et al. Use of active personal dosemeters in interventional radiology/cardiology: Tests in laboratory conditions and recommendations—ORAMED PROJECT*. Radiat. Meas. **46**(11), 1252–1257 (2011).
8. Vanhavere, F., Carinou, E., Gualdrini, G., Clairand, I., Sans Merce, M., Ginjaume, M. *et al. ORAMED: optimisation of radiation protection of medical staff*. In: EURADOS Report, 2012–2002. (2012).
9. Klammer, J., Roth, J. and Hupe, O. *Novel reference radiation field for pulsed photon radiation installed at PTB*. Radiat. Prot. Dosim. **151**(3), 478–482 (2012).
10. Zutz, H., Hupe, O., Ambrosi, P. and Klammer, J. *Dtermination fo relevant parameters for the use of electronic dosemeters in pulsed fields of ionising radiation*. Radiat. Prot. Dosim. **151**(3), 403–410 (2012).
11. Ciraj-Bjelac, O., Carinou, E. and Vanhavere, F. *Use of active personal dosimeters in hospitals: EURADOS survey*. J. Radiol. Prot. **38**, 702 (2018).
12. Ginjaume, M. *et al. Effect of the radiation protective apron on the calibration of active and passive personal dosemeters used in interventional radiology and cardiology*. J. Radiol. Prot. **39**, 97–112 (2019).
13. International Organization for Standardization. *Radiological protection—characteristics of reference pulsed radiation—Part 1: photon radiation*. In: Technical Specification ISO/TS. pp. 18090–18091 (2015).
14. Hupe, O., Zutz, H. and Klammer, J.. *Radiation protection dosimetry in pulsed radiation fields*. www.irpa.net/members/TS2f.3.pdf, IRPA 2012 conference, Glasgow (2012).
15. Hupe, O., Friedrich, S., Brodecki, M. and Vanhavere, F. *Determining the dose rate dependence of different active personal dosemeters in standardised pulsed and continuous radiation fields*. Submitted to Radiation Protection Dosimetry ID RPD-18-0528 (20.12.2018).
16. International Electrotechnical Commission. Radiation protection instrumentation—measurement of personal dose equivalents Hp(10) and Hp(0,07) for X, gamma, neutron and beta radiations—direct reading personal dose equivalent metersIEC 61526 Ed.3. (2010).
17. Krzanovic, N., Zivanovic, M., Ciraj-Bjelca, O., Lazarevic, D., Ceklic, S. and Stankovic, S. *Performance testing of selected dosimeters in X- and gamma radiation fields*. Health Phys. **113**(4), 252–261 (2011).
18. International Commission on Radoation Protection. General Principles for the Radiation Protection of Workers. Ann. ICRP **27**(1), (ICRP Publication 75) (1997).