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D7 Future standardization needs related to new and upcoming technologies in personal dosimetry

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TABLE OF CONTENTS

1 Overview of new and upcoming technologies in personal dosimetry

Passive personal dosimetry has been the golden standard for official personal dose monitoring of exposed workers to ionizing radiation for many decades. Passive dosemeters do not provide direct dose information on a screen or an alarm function and need to be send back to an official dosimetry laboratory for read-out and analysis before the doses can be retrieved. The whole process between sending back the dosemeters and receiving the dose report can take a few weeks or even more than a month. This lack of direct feedback is a disadvantage that limits the potential for reducing the doses as much as possible according to the ALARA principle.

Since a few decades, active personal dosemeters are allowed to be used, in some countries, as official dosimetry system, recognized by national regulatory body. In contrast to passive personal dosemeters, active personal dosemeters do provide real-time dose information on the screen, as well as an alarm function. This can help substantially to apply the ALARA principle. Active personal dosemeters can dosimetrically perform equally well or even better than passive personal dosemeters, but they are quite expensive, have a limited battery life and can have problems in high dose rate or pulsed radiation fields. This limits their use to a restricted number of workplaces.

Roughly after 2010, hybrid personal dosemeters have been introduced as official personal dosemeter at some facilities. These hybrid dosemeters usually use integrating detectors, but have direct on site or even built-in reading capability. So, they don’t need to be sent back to the dosimetry laboratory for read-out and analysis. Hybrid dosemeters can provide near real-time dose information, are cheaper than active dosemeters and have a longer battery life. However, they do not provide real-time dose information on a screen or an alarm function. Hence, hybrid personal dosemeters are a bit in between passive and active personal dosemeters.

All manufactured personal dosemeters have important limitations. They provide only point measurements at the wearing location and they provide measurements in terms of operational quantities that only provide a conservative estimate of the protection quantities of interest. Their response in terms of these operational quantities as a function of radiation type, energy and incident angle usually is far from perfect. There are also several practical issues in the field of personal dose monitoring such as forgetting to wear the dosemeter, wearing it incorrectly or losing it. Therefore, in the last few years there has been ongoing research to investigate the possibility of replacing the well-known personal dosimetry based upon physical personal dosemeters by computational personal dosimetry.

A more detailed recent overview of the current trends in personal dosimetry can be found in (Vanhavere & Van Hoey, 2022). This section gives a short overview of the relevant new and upcoming technologies in personal dosimetry based on a literature review and private communication with personal dosemeter manufacturers.

1.1 Dosepix novel active personal dosemeter

In response to the limitations of current active personal dosemeters in high intensity and pulsed radiation fields, the Dosepix is being developed based on a novel approach. Dosepix based dosemeters consisting of three pixelated semiconductor Dosepix detectors under different filters have been developed. The Dosepix detector technology is similar to the well-established Medipix/Timepix technology. First tests with the Dosepix based dosemeters demonstrated compliance with the German type testing criteria for energy response, angular response and coefficient of variation (Haag, et al., Personal Dosimetry in Continuous Photon Radiation Fields With the Dosepix Detector, 2021). The dead-time-free readout mechanism of the Dosepix allows it to perform well in fields with dose rates up to 70 Sv/h (Haag, et al., Personal Dosimetry in Direct Pulsed Photon Fields With the Dosepix Detector, 2022). This feature makes this active personal dosemeter very promising for use in the pulsed fields of interventional radiology, where current active personal dosemeters can have a significant under-response.

1.2 Hybrid dosemeters

Production of hybrid dosemeters started about 30 years ago with the RADOS hybrid dosemeters based on direct ion storage. These dosemeters were read out by means of a compact reader that allowed on site readout.

Mirion has proceeded with this technology with its Instadose® dosemeters. The Instadose dosemeters provide internal readout of the voltage over the channel of the transistor to assess the accumulated dose. The first version of the Instadose® dosemeters transferred its data by a computer with accompanying software by plugging in the USB port of the dosemeter. The two advanced models Instadose®+ and Instadose®2 dosemeters transfer their data wirelessly through Bluetooth using a USB Bluetooth communicator plugged into a computer, a Bluetooth communicator directly plugged into the local network or a smartphone with accompanying application. Readouts can be preprogrammed, for instance every week or every month, or on demand by pushing the button on the back of the dosemeter. The Mirion Instadose®+ and Instadose®2 dosemeters are currently being used as official accredited personal dosemeter in different countries. They comply with

the type testing criteria of the IEC 62387:2020 standard for passive personal dosemeters according to the tests performed by the dosimetry laboratories in these countries.
In the recent years, Mirion developed the Instadose® Vue, an updated Instadose® dosemeter with a screen displaying useful information for the users. It is still not an active dosemeter, as assessment of the accumulated dose still requires preprogramming or manual reading. Thermo Fisher Scientific recently brought the NetDose hybrid dosemeter on the market in the United States through RDC. Private communications showed that also other manufacturers, such as Landauer and HERADO (ALMAR dosemeter) have developed or are developing hybrid or cheap active dosemeters. So, it can be expected that more hybrid or cheap active dosemeters will come on the market soon.

1.3 Spectrodosemeters

Measurements with physical dosemeters are based on converting the signal delivered by the dosemeter sensor to the operational quantity of interest through calibration. If the variation of the signal delivered by the sensor as a function of the energy and angle of incidence of the radiation is identical to that of the conversion coefficient from fluence to the operational quantity, as tabulated in ICRU 57, then a single calibration coefficient can be used regardless of the energy and angle of incidence of the radiation.

Unfortunately, in practice this ideal scenario does not reflect reality. The sensors' intrinsic response differs from the variation in the ICRU 57 conversion coefficients. This problem can be tackled in different ways. Often this is done by adding shielding around the sensor to improve the energy and angular response. Another possibility is to obtain information about the energy spectrum of the radiation field to correct for the sensor's imperfect energy response. A spectrometer can facilitate this correction. The term spectrodosemeter is used if the dosemeter has an on-board spectrometer that can provide spectral information to apply the necessary energy correction.
Note that often passive stimulated luminescence or film dosemeters implement the spectrodosimetry principle by using multiple sensors or a single sensor with multiple energy measurement ranges, using filters of varying attenuation to cover the entire energy range to be measured. A fixed linear algorithm or a branching algorithm is then used to calculate the operational quantity of interest based on the signals from the different sensors or energy ranges. Also the Dosepix is a multi-element dosemeter that provides very rough spectral information through its three sensors with different filters.
Similarly, if the sensor of an electronic dosemeter can deliver a signal proportional to the energy of the incident radiation, separate signals covering different parts of the energy range can be obtained with a single sensor. The algorithm for calculating the operational quantity, based on signal analysis, enables the calibration coefficient to be adapted to the spectrum encountered. This principle is already in use for instance in several national dosimetry networks deployed for early-warning in case of radiological incidents.

A spectrodosemeter is a dosemeter that allows assessment of the operational quantity based on detailed knowledge of the spectrum at the measurement point. The operational quantity H is equal to the scalar product of the fluence energy spectrum $\phi(E)$ at the measurement point and the energy dependent conversion coefficient $h_{\phi}(E)$ from the fluence to the operational quantity according to ICRU 57, as shown in equation 1.

$$H = \sum_E h_{\phi}(E)\phi(E) \qquad (1)$$

This spectrometric method can be used for all types of radiation, but the scope in this project is limited to photon dosimetry. Currently, some manufacturers claim the spectrodosimetric method for photon dosemeters used in early warning networks, portable or hand-held instruments and to our knowledge, for one individual dosimetry system.
The spectrometric method implies that the raw photon spectrum provided by the sensor is corrected for the sensor's detection efficiency and for artefacts resulting from the disturbance it introduces to the radiation field, such as intrinsic self-background and dead time. In this case, the result is more accurate in terms of operational quantities, since the calculation method is identical to the theoretical method. If the conversion coefficients are modified or the operational quantities are changed, a great advantage is that only the conversion coefficient matrix needs to be changed, not the hardware of the dosemeter.

In theory the spectrometric method has many advantages. However, implementing corrections on the raw spectrum is costly in terms of power supply and memory consumption. Consequently, the method is rarely used for portable devices such as personal dosemeters at present, but it can more easily be implemented for environmental measurements, such as those carried out by early warning networks. Consequently, an increasing number of devices used in early warning networks are employing this method to assess operational quantities.

To limit manufacturing costs and energy consumption, it is reasonable to question the level of detail required for the spectrum to provide an evaluation of the operational quantity that meets the criteria of type test standards, particularly regarding the energy response. Theoretical calculations of operational quantities as a function of photon spectrum discretization show that around ten channels are sufficient for the required precision and accuracy. The error introduced by decreasing the number of channels to about ten is below 5%. The reason for this is that the conversion coefficients in ICRU 57 have a smooth energy dependence without discontinuities.

The main difficulty in applying the spectrometric method is properly correcting the raw energy spectrum $S_b(E)$. In fact, the calculation of the operational quantity is more complicated because the sensor's detection efficiency $N_\phi(E)$ must be introduced into the calculation, as shown in equation 2. $N_\phi(E)$ is a calibration coefficient in terms of fluence. The product $h_\phi(E)N_\phi(E)$ is a calibration coefficient in terms of the operational quantity.

$$H = \sum_E h_\phi(E)N_\phi(E)S_b(E) \qquad (2)$$

In equation 2, the product $N_\phi(E)S_b(E)$ is only equal to $\phi(E)$ if artifact corrections have been made to the raw spectrum $S_b(E)$. These corrections should include for instance escape, backscatter peak, fluorescence on dosemeter components, pile-up and inherent background. It is therefore necessary to introduce a spectrum "cleaning" correction, $C\left(S_b(E)\right)$, which depends on the energy spectrum at the point of measurement as shown in equation 3.

$$H = \sum_E h_\phi(E)\, N_\phi(E) \left(S_b(E) - C\left(S_b(E)\right)\right) \qquad (3)$$

Finally, the range of dose equivalent rates that a dosemeter must be able to measure is very wide. For example, the IEC 60846-2 standard covers a range up to 10 Sv/h and IEC 61526 up to 1 Sv/h. Linearity as a function of dose rate is impacted as soon as a sensor and its associated electronics have a non-negligible dead time. Therefore, a linearity correction must be included in the dose equivalent calculation. However, unlike a dosemeter using a GM tube, for example, a spectrodosemeter's dead time affects not only the ability to record two pulses close together, but also the spectrometer's energy calibration at high count rates. This is because it induces a shift in the spectrum towards lower energies. The high count rate moves up the base line of the pulse, leading to a decrease of the pulse height. The pulses are then registered in lower channel, which in turn affects the channel-by-channel calculation of the operational quantity. Two dead time corrections must be added: one to correct for counting loss (TM1) and the other to correct for pulse amplitude changes (TM2). Assuming that the dead time affects the entire spectrum uniformly, TM1 is a simple multiplicative factor. These corrections are added in equation (4)

$$H = \sum_E h_\phi(E)\, N_\phi(E) \left(S_b(E) - C\left(S_b(E)\right)\right) TM1\left(S_b(E)\right)\, TM2\left(S_b(E)\right) \qquad (4)$$

The strict application of the spectrometric method is highly complex and requires the deconvolution of the raw spectrum. However, some authors suggest working with the raw spectrum without deconvolution for environmental measurements involving low ambient dose equivalent rates or negligible dead time effects according to equation 5.

$$H = \sum_E N_h(E)\, S_b(E) \qquad (5)$$

The idea in equation 5 is to link the raw spectrum directly to the dose equivalent, thereby enabling measurement artefacts to be corrected by bypassing the intermediate steps of equations 3 and 4, so that the result of equation 5 is the same as that of equation 3. $N_h(E)$ is a function that encompasses all corrections. It is defined during manufacturer calibration by a matrix calculation on a reduced number of channels based on the comparison of the $\phi(E)$ and $S_b(E)$ spectra. However, $N_h(E)$ is strictly valid only under the conditions the detector was calibrated in.

The question is how to determine the spectrometric nature of this method. Ultimately, this comes down to adopting an algorithm to calculate the operational quantity as a function of signals from different energy ranges, as is already the case for some passive dosemeters. To improve the accuracy of dose equivalent calculations, variable channel widths could be used depending on the variation in fluence to dose equivalent conversion coefficients. Having a greater number of channels in zones where the conversion coefficient varies the most, would enable more accurate calculations.

The method based on equation 5 assumes that the dosemeter response is constant at any dose equivalent rate, as defined in type test standards for radiation meters. Figure 1 shows that, even at relatively low dose rates (which are, however, higher than those typically encountered in environmental measurements), there is a shift in the spectrum towards lower energies. Therefore, for detectors subject to non-negligible dead times, a correction must be introduced for the influence of the dead time on both the number of pulses recorded and the energy calibration, as in equation 4. This correction is particularly challenging for operational dosemeters, for which autonomy is an important issue. In principle, the identifiable peaks in energy spectrum could be used for stabilization, but this again requires additional computational power.

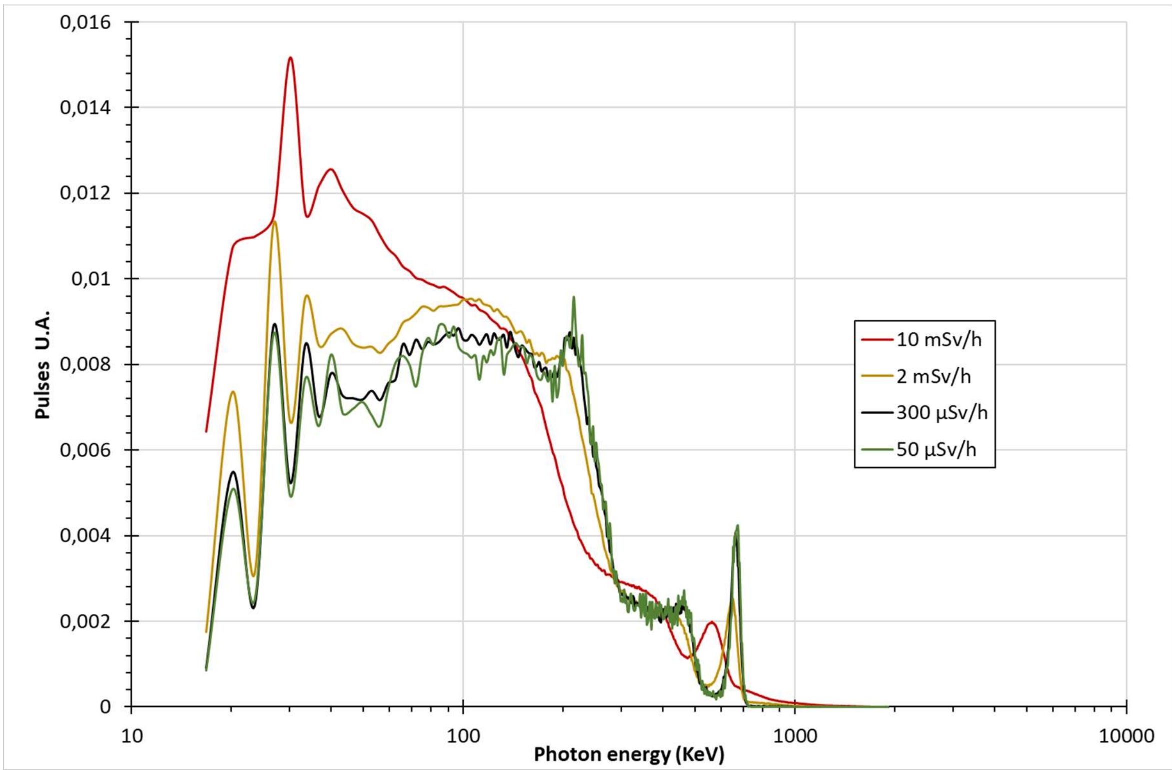

Figure 1: Raw spectra achieved with a Icohup Rium OP operational dosemeters for a ^{137}Cs collimated beam for different personal dose equivalent rate.

The calibration procedure implemented by the manufacturer includes two main stages: energy calibration and dose equivalent calibration. The latter is highly dependent on the former, since a shift in the raw spectrum will lead to a systematic error in the dose equivalent value. This is because, when the content of each channel no longer corresponds to the expected energy range, errors will be introduced in the calculation of $N_h(E)$. It should be noted that some spectrometers are sensitive to temperature changes as well, so using them outdoors or in another varying environment may cause additional uncertainties to dose equivalent readings.

Like all dosemeters, spectrodosemeters require periodic calibration checks. The procedure for checking and correcting calibration depends on access to the internal settings and, possibly, the algorithm for calculating the operational quantity. If access to the latter is available, the detection efficiency curve can be checked over the entire energy domain and readjusted if necessary. Otherwise, a simple procedure using a single radiation quality can be used to adjust the efficiency curve homothetically.

1.4 Computational dosimetry

The PODIUM H2020 project investigated for the first time the potential of replacing physical personal dosemeters by computational dosimetry. The idea is to combine monitoring of worker movements and postures using 3D cameras and skeleton tracking algorithms, computational anthropomorphic phantoms, models of the workplace and the radiation source and Monte Carlo radiation transport simulations to calculate the operational and protection quantities. This approach has the potential to get rid of the limitations of physical dosemeters. Instead of an imperfect point measurement in terms of operational quantities obtained with physical dosemeters, this method allows to directly assess the protection quantities of interest. Furthermore, if the calculations can be performed sufficiently fast, real-time feedback on the received doses and alarm function are possible. Due to the digital nature of this methodology, it could provide visualization of the radiation field by means of virtual or augmented reality. This can be very beneficial for training purposes and as a tool to implement the ALARA principle.

The PODIUM project focused on two applications where physical dosemeters have important limitations: interventional radiology because of the strong dose gradients and neutron workplace fields because of the bad performance of neutron dosemeters in comparison with photon dosemeters. Proof of concept was demonstrated both for interventional radiology (Abdelrahman, et al., 2020), (Almén, et al., 2021), (O'Connor, et al., 2022) and neutron workplace fields (Eakins, et al., 2021), (Van Hoey, et al., 2022). However, also important challenges were identified. The Monte Carlo simulations are computationally very demanding, and it was concluded that more effort is needed to speed up the simulations. Also, the inclusion of movable objects, influencing the radiation exposure, like shielding in interventional radiology, proved to be an area for future improvements.

The PODIUM project was the onset for the future and still ongoing research in the field of computational dosimetry. At UPC in Spain a fast GPU based Monte Carlo code MCGPU-IR was developed specifically for interventional radiology (Balcaza, et al., 2023). At Université de Bretagne Occidentale in France another approach to speed up the dose calculations was investigated. They used Deep Learning (DL) and more specifically Convolutional Neural Networks (CNN) trained with a database created by Monte Carlo simulations (Villa Arias, 2023). The Belgian Nuclear Research Center SCK CEN that coordinated the PODIUM project is also still performing research on computational dosimetry in the fields of interventional radiology, nuclear medicine, nuclear decommissioning and neutron workplace fields. Furthermore, also research groups outside the PODIUM consortium such as Hanyang University in the Republic of Korea and PTB together with the Technical University of Braunschweig in Germany now started working in the field of computational dosimetry. The latter resulted already in a publication on the speedup of Monte Carlo simulations using neural networks (Lehner, Lombardo, Castillo, Hupe, & Magnor, 2025). Hence, computational personal dosimetry as replacement for physical personal dosemeters is a growing research field that might completely reshape operational personal dosimetry of radiation workers in the future.

1.5 Artificial intelligence

Nowadays, the use of artificial intelligence (AI) is growing in many fields, also in dosimetry. A literature study was performed to obtain an overview of the current use of AI in dosimetry.

Two studies investigated the use of neural networks (NNs) for spectral unfolding in neutron dosimetry (García-Baonza, et al., 2023), (Drejzin, Grimov, & Logvinov, 2016). This approach could be used also for photon spectrodosemeters. For multi-element photon thermoluminescent dosemeters machine learning (ML) was implemented in three studies for improving the dose calculation algorithm (Pathan, Pradhan, Selvam, & Sapra, 2024), (Lee S. , Kim, Jung, & Lim, 2024), (Lee, Kim, & Lee, 2001). NNs were also used for direct assessment of H*(10) from the gamma spectrum measured with a plastic scintillator (Hwang, Jeon, Kim, Kim, & Cho, 2022). Hence, it can be expected that dose calculation algorithms will in the future more commonly be based on ML and NNs.

NNs were also used for the Dosepix detector. The use of NNs allowed to speed up the energy calibration procedure (Schmidt, 2021) and to assess the dose in pulsed photon fields (Hufschmidt, 2022).

AI was also investigated in several studies to improve the quality control in dosimetry services. It was used for instance to aid identification of anomalous TLD glow curves (Amit, Vagerman, & Revayev, 2024), (Arquero, Berenguer-Antequera, & Benavente, 2024) and for estimation of the irradiation date from TLD glow curves (Mentzel, et al., 2021). Furthermore, three studies tried to predict radiation doses based on historical data and information about the exposure situation (Balanya, Ramos, & Ramirez-Hereza, 2022), (Meades, Page, Ross, & McCool, 2023), (Troville, Rudin, & Bednarek, 2021). Also, at SCK CEN an unpublished study was performed in which NNs were used to predict the likelihood of receiving a significant dose based on different parameters. Such dose predictions can also help in the quality control of dosimetry services.

In computational dosimetry NNs trained by Monte Carlo radiation transport simulations have the potential to predict dose distributions without requiring computationally intensive simulations. This was already discussed in more detail in the previous section.

2 Future standardization needs

2.1 Passive personal dosemeters

For passive personal dosemeters type testing guidance is provided by the following IEC standard:

IEC 62387:2020, Radiation protection instrumentation - Dosimetry systems with integrating passive detectors for individual, workplace and environmental monitoring of photon and beta radiation

As no significantly new technologies are upcoming for passive personal dosemeters, no update is currently required for this standard. However, as hybrid dosemeters are now explicitly added under the scope of IEC 61526:2024 and should thus be tested according to this standard, the text “and may contain electronic components, e.g. for the readout (e.g., in a direct ion storage (DIS) dosemeter)” on page 9 bullet point b should be removed to avoid confusion.

2.2 Active and hybrid personal dosemeters

For active personal dosemeters type testing guidance is provided by the following IEC standard:

IEC 61526:2024, Radiation protection instrumentation – Measurement of personal dose equivalents for X, gamma, neutron and beta radiations – Active personal dosemeters

This standard was recently updated starting from the previous version from 2010. Since this latest version of the standard, it applies to both direct reading and hybrid dosemeters. So, it is now made explicit that hybrid dosemeters should be tested according to this standard and not according to IEC 62387:2020 for passive dosemeters.

Testing of hybrid dosemeters has demonstrated in several labs that some effects of exposure to environmental conditions such as humidity and temperature seem to occur only after long-term exposure of the order of weeks or months. Furthermore, as hybrid dosemeters usually stay long time on site without the possibility of recalibration, changes in sensitivity might occur over this time on site. Testing of such long-term effects is currently not included in IEC 61526:2024 and might also be difficult to incorporate because long term tests are very difficult to perform in practice for manufacturers. This is an important issue to consider for future updates of the IEC type testing standards, because such effects might lead to inaccurate dose assessment for some dosemeters under specific conditions. Furthermore, such effects or part of such effects might also be relevant for passive and direct reading active dosemeters.

The latest hybrid dosemeters have internal readout and transfer their data automatically and wirelessly. Therefore, it might be relevant to include in a future version of the IEC 61526 type testing standard also a more detailed section on connectivity and data security of such devices with automatic data transfer with reference to relevant standards dealing with such aspects, such as WELMEC Guide 7.2.

In current type testing standards, the testing of dose rate dependence and energy and angular dependence is performed independently. However, for complex detectors such as the Dosepix, the assumption of independence of these effects is no longer valid. That is something that should be dealt with in a future version of the IEC 61526 type testing standard.
A recent study at PTB (Ketelhut, Zutz, & Hupe, 2024) has demonstrated that inductive chargers can have a very strong influence on active personal dosemeters with doses up to several tens of mSv in 20 seconds. The electromagnetic fields produced by such inductive chargers are not included in the IEC standard. So, it is important to include tests with such electromagnetic fields as soon as possible in the IEC standards.

As currently new developments in active and hybrid dosemeters are ongoing, it is recommended that this standard is periodically evaluated for potential required updates to keep up with these new developments.

2.3 Pulsed radiation fields

For pulsed radiation fields type testing guidance is provided by the following IEC standard:

IEC TS 63050:2019, Radiation protection instrumentation – Dosemeters for pulsed fields of ionizing radiation

This IEC standard defines tests with relatively long pulse durations in comparison with pulse durations encountered in real workplaces. This was decided based upon the availability of testing facilities. Therefore, development of testing facilities with shorter pulse durations and adaptation of the tests in the IEC TS 63050 standard when such facilities will be available is recommended.

2.4 Spectrodosemeters

In section 1.3, it was discussed that the three main dosimetric characteristics are energy response, angular response and dose rate linearity. The use of the spectrometric method has little or no effect on the angular response, which primarily depends on the shape of the sensor and the filters that can be added around it. Spectrodosemeters are expected to exhibit a better energy response. However, when using only a limited number of channels (less than 10), the energy response will not be better than the usual algorithmic treatments based on multi-sensor or multi-filter dosemeters.

Therefore, it does not seem necessary to adapt the test criteria to account for the introduction of the spectrometric method for angular and energy responses. It would be better to wait until a real improvement in the performance of spectrometric dosemeters compared with existing ones can be demonstrated before modifying the standard criteria.

Dose rate linearity is more problematic, however, due to dead time influencing not only the number of events recorded but also energy calibration. Table 1 summarizes the dose equivalent rate ranges for the linearity test in the standards dealing with type tests for active dosemeters.

Table 1: Dose equivalent rate range considered for the linearity test

Standard number	Title	Dose equivalent range
IEC 62327	Hand-held instrument for detection and identification of radionuclides and for estimation of ambient dose equivalent rate for photon radiation	*H**(10): 1 µSv/h to manufacturer-stated maximum. (10 µSv/h is mentioned for the standard test conditions)
IEC 60846-1	Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation – Part 1: Portable workplace and environmental meters and monitors	*H**(10): 3 µSv/h to 100 µSv/h
IEC 60846-2	Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation - Part 2: High range beta and photon dose and dose rate portable instruments for emergency radiation protection purposes	*H**(10): 1 mSv/h to 10 Sv/h
IEC 61526	Measurement of personal dose equivalents for X, gamma, neutron and beta radiations - Active personal dosemeters	*Hp*(10): 0.1 mSv/h to 1 Sv/h or manufacturer-stated maximum. (10 mSv/h is mentioned for the standard test conditions)
IEC 60532	Installed dose rate meters, warning assemblies and monitors - X and gamma radiation of energy between 50 keV and 7 MeV	Manufacturer-stated range

IEC 61017	Radiation protection instrumentation - Transportable, mobile or installed equipment to measure photon radiation for environmental monitoring	$H^*(10)$: 30 nSv/h to 30 µSv/h

As shown in Table 1, the six standards cover all existing devices and applications, meaning there is no need for a specific standard for dosemeters using the spectrometric method. However, it is advisable to harmonize the requirements for similar applications and to clearly define the area of application (scope). Of the criteria associated with the tests described in the standards, the criterion relating to linearity is the least well-defined in terms of the dose equivalent rate range to be explored. This range normally varies according to the application, but standards 62627 and 60532 simply leave it to the manufacturer to choose the range or one of the dose equivalent rate bounds. However, unlike dosemeters using GM detectors, which can be blinded by pulsed radiation fields of the medical diagnostic type, the loss of information due to the dosimetric method in this case appears to be more gradual and, therefore, less easy to put into evidence. In this context, a minimum range should be introduced, allowing manufacturers to go further if they can.

Concerning the calibration procedure, bear in mind that the information delivered by the dosemeter is either an integrated dose equivalent or a dose equivalent rate. As the calibration laboratory only has global information on the value of the operational quantity, the calibration/verification procedure remains identical to the current one. If one has access to the measured spectra, however, a more precise diagnosis can be provided if the results differ from those claimed by the manufacturer.

2.5 Computational personal dosimetry

For the computational personal dosimetry approach, there are currently no general standards available. Therefore, there is currently no framework to deal with accreditation, approval and traceability in case of computational personal dosimetry. One exception is aircrew dosimetry. Aircrew doses are normally monitored using calculation codes and there are standards recommending that approach and providing guidelines. Hence, the standardization approach computational personal dosimetry could be based on the approach used for aircrew dosimetry.

The ICRP guidelines for aircrew dosimetry are provided in the following document:

ICRP, ICRP Publication 132, Radiological Protection from Cosmic Radiation in Aviation, Annals of the ICRP, Volume 45, No. 1, 2016

This document discusses the exposure of aircrew and recommends the use of calculation codes validated by measurements in planes for aircrew dose assessment.

The European Commission also published a document providing a comparison of measurements and calculations of aircrew doses:

European Commission, Radiation Protection 140, Cosmic Radiation Exposure of Aircraft Crew: Compilation of Measured and Calculated Data, European Commission, 2004

This study performed by EURADOS demonstrates that the measurement techniques and calculation codes are sufficiently accurate and in good agreement with each other.

EURADOS has also performed another study, comparing different aircrew dose assessment codes, showing good agreement:

EURADOS, EURADOS Report 2012-03, Comparison of Codes Assessing Radiation Exposure of Aircraft Crew due to Galactic Cosmic Radiation

ISO has published a series of standards providing guidelines for validation measurements of aircrew dose calculations:

ISO, ISO 20785-1:2020, Dosimetry for exposures to cosmic radiation in civilian aircraft – Part 1: Conceptual basis for measurements, 2020
ISO, ISO 20785-2:2020, Dosimetry for exposures to cosmic radiation in civilian aircraft – Part 2: Characterization of instrument response, 2020
ISO, ISO 20785-3:2023, Dosimetry for exposures to cosmic radiation in civilian aircraft – Part 3: Measurements at aviation altitudes, 2023

PTB has performed validation of software tools by a dedicated measurement campaign to get approval for the computational method in Germany.

Analogous to this approach used for aircrew dosimetry, it is proposed to consider the combination of a Radiation Protection document by the European Commission providing guidelines and recommendations on the use of computational personal dosimetry and an ISO standard to provide practical guidelines for validating computational personal dosimetry frameworks for specific workplaces. The ISO standard will be an essential document, while the European Commission document will only be for guidance and thus less essential. So, it is also a possibility to aim for the ISO standard only and incorporate the items of the proposed European Commission document in that standard. The following elements could be included in these documents:

- Radiation Protection document by the European Commission
    - Personal dosimetry using physical personal dosemeters has significant limitations such as the measurement in terms of imperfect operational quantities, the imperfect response in terms of operational quantities, the fact that it is a point measurement and the risk for loss or incorrect wearing of the dosemeter.
    - Personal dosimetry with physical personal dosemeters can lead to significant under- or overestimations of the doses received by workers.
    - Current technology enables (quasi) real-time calculation of worker doses by tracking them with cameras and using Monte Carlo radiation transport or other simulation codes, if necessary, in combination with machine learning algorithms.
    - Computational personal dosimetry can in some applications lead to significantly more precise worker dose assessment and thus to better protection of the workers. It also has the potential to improve the application of the ALARA principle by real-time and detailed feedback on the radiation exposure.
- ISO standard
    - The radiation field must be characterized with sufficient detail to allow computational personal dosimetry with at least the precision required for physical personal dosemeters.
    - The characterization of the radiation field should be performed with calibrated detectors in terms of operational quantities with traceability to a primary standard or by simulations validated by such measurements.
    - A camera system should be installed in such a way that all workers can be identified and monitored with a spatial resolution that is sufficient to allow personal dosimetry with at least the required precision for physical personal dosemeters, considering the dose rate gradients in the radiation field.
    - A validation of the whole system should be performed, comparing the calculated doses with doses measured with reliable physical personal dosemeters.
    - If the radiation field fluctuates in time, the computational dosimetry system should be coupled with a radiation measurement system to consider the time fluctuations. Also in a stable radiation field, quality control measurements should be performed on a regular basis to confirm the stability of the radiation field.

2.6 Artificial intelligence

Currently, the use of AI in routine dosimetry is still very limited. However, this could increase soon. Based on existing literature, the most probable future fields of application in routine dosimetry are in spectral unfolding and quality control for physical dosimetry systems and in speed-up of dose calculations in computational dosimetry.

The use of AI for spectral unfolding and in the dose calculation algorithm does not change current practices fundamentally. There are currently also other non-linear algorithms used in the dose calculation. This is covered in existing type testing standards by demanding that in case of such algorithms, the response of the dosemeters should also be evaluated for mixed radiation fields to demonstrate the absence of significant anomalies for some mixtures. If this evaluation is carefully done according to the existing standards, potential problems with the AI-based dose calculation algorithms should be identified.

The use of AI in support of quality control will only be beneficial for the quality of the dosimetry services. No specific standardization needs could be identified related to this application.

When using AI to speed-up dose calculations in computational dosimetry, it will be very important to demonstrate the reliability of the method. Hence, in future standards on computational dosimetry the use and quality control of AI should be discussed in detail to guarantee reliable dosimetry.

2.7 Feedback from Mirion as manufacturer

The presence of Mirion as project partner gave the chance to get direct feedback on the future standardization needs also from the manufacturer side. At Mirion in Finland they are mostly working with the following two standards:

- IEC 69846-1:2009 Radiation protection instrumentation - Ambient and/or directional dose equivalent (rate) meters and/or monitors for beta, X and gamma radiation - Part 1: Portable workplace and environmental meters and monitors
- IEC 61526:2024 Radiation protection instrumentation - Measurement of personal dose equivalents for X, gamma, neutron and beta radiations - Active personal dosemeters

Based on their experience of type testing dosemeters against these standards as manufacturer, they provided detailed feedback. Their detailed feedback can be found in the Excel table that was added as appendix to this deliverable. Some of the more general comments can be summarized as follows:

- It is crucial that the requirements in the standards are clear and unambiguous. Currently some of the requirements are ambiguous.
- Currently some of the requirements are contradictory to each other.
- The test methods should be as simple as possible.
- Some tests methods are contradictory to radiation protection requirements (e.g. need to store radioactive sources in very humid environment) as requirements for sources have tightened over the years.
- Standards don’t fully consider the digital features of the devices, which are developed nowadays.

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