EURADOS

European Radiation Dosimetry Group e. V.

EURADOS Report 2022-02

Neuherberg, July 2022

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Content:

Abstract

The International Commissions on Radiation Units and Measurements (ICRU) and on Radiological Protection (ICRP) have published a joint report, as ICRU Report 95, recommending new operational quantities for use in radiological protection. The new quantities have been devised to address known problems with the existing ones, including the need to cover a wider range of radiation types and energies, for example arising from the increasing use of proton therapy in clinical procedures. Also related to changing practices is the increased importance of doses at diagnostic x-ray energies below about 80 keV, where the more frequent use of interventional procedures renders less acceptable the over-estimation given by the existing quantities. The new operational quantities are conceptually different from the existing ones, being defined using the same anthropomorphic voxel phantoms as are used to derive the protection quantities. ICRP have carried out a consultation process and ICRU have revised the report in the light of comments received.

As part of its strategic research agenda, EURADOS seeks to contribute to the development and understanding of fundamental dose concepts, such as the topic of operational quantities. Accordingly, we have carried out a project to evaluate the impact of the proposed quantities and to make recommendations for their application. The task group included experts drawn from across the various EURADOS working groups.

This report analyses the differences between the new and existing quantities before going on to examine the impact and application in the areas of: radiation protection practice, dosemeter and instrument design, calibration and reference fields, European and national regulation, and current published standards.

The new quantities will achieve the benefits of wider radiation type and energy coverage, and of improving representativeness in the diagnostic/ interventional photon energy range. The biggest negative impact will be in the area of dosemeter and instrument design. Here, the changes needed to achieve good responses to the new operational quantities will range from simple re-calibration to radical re-design; and some types of dosemeter may become obsolete. Significant investments are therefore required to achieve the aforementioned benefits.

We support the recommendation that the introduction of the new quantities should be phased over tens of years. Not only will this provide time for the costs and benefits to be fully assessed and the necessary research to be carried out, it will also allow for consideration of the parallel development of the planned new recommendations from ICRP.

1. Introduction and Scope

1.1. EURADOS

The European Radiation Dosimetry Group (EURADOS) is a voluntary network of over 80 institutions from across Europe, supported by nearly 600 individual scientists. As a non-profit organization, EURADOS promotes research, development and European cooperation in the field of ionizing radiation dosimetry. It maintains a network which includes experts, reference and research laboratories, universities and dosimetry services. This enables appropriate specialist groups to be formed in a timely manner to solve problems or promote research identified within EURADOS or upon request from external bodies. Details of how EURADOS operates can be found on its website, www.eurados.org.

Since its inception in 1982, EURADOS has established a reputation both within and outside Europe as an important and respected resource for radiation dosimetry expertise. Its work is widely and regularly disseminated at international conferences, workshops and training courses, and a wide range of laboratories takes part in the various intercomparisons that EURADOS regularly organises. The current work plan follows the EURADOS Strategic Research Agenda (SRA) (Bottollier-Depois *et al*, 2020).

The SRA identifies several research areas, or "visions", concerning:

- updated fundamental dose concepts and quantities;
- improved radiation risk estimates deduced from epidemiological cohorts;
- efficient dose assessment for radiological emergencies,
- integrated personalized dosimetry in medical applications; and
- improved radiation protection of workers and the public.

In addition, it describes the need for continued activities in harmonisation, education and training. It is under the first of the visions, regarding fundamental dose quantities, that EURADOS has undertaken the present work. Specifically, within its Vision "Towards updated fundamental dose concepts and quantities", EURADOS identifies the challenge "To Improve the protection and operational quantities used in dosimetry" in which the objectives are as follows (Bottollier-Depois *et al*, 2020):

"The overall objective is to improve the utility of the dose quantities in terms of their applicability, their ease of use and their relation to detriment.

- *To promote wide understanding of the concepts, application and limitations of the protection and operational quantities.*
- *To promote research that supports greater understanding of the quantities.*
- *To identify opportunities for improving the quantities in future revisions.*

These objectives will require dialogue with the radiation protection community together with physical and calculational research."

EURADOS Working Groups (WGs) are involved in research on several aspects of dosimetry of ionizing radiation including individual monitoring, environmental, internal, retrospective, medical and computational dosimetry. The results of this work are published in peer-reviewed journals and, since 2012, in the series of EURADOS reports. EURADOS expertise enables to contribute to the discussions on the science-based policy implications.

The recent publication of the joint ICRU/ICRP Report 95, Operational Quantities for External Radiation Exposure (2020) proposed to significantly modify more than 30 years-old approach to measure radiation protection quantities, based partly on the concept of the ICRU sphere.

The objective of this EURADOS report is to discuss the implications of the newly proposed quantities for the techniques of dose measurements and for the regulations in radiation protection.

1.2. Protection Quantities, Operational Quantities and Field Quantities

In the system of radiological protection, **protection quantities** are those devised to represent the health detriment to individuals resulting from the energy deposition per unit mass. They account for the relative effectiveness of different types of radiation and the relative radiosensitivity of various human tissues and organs, and they are based on representative models of the human body. It is the **International Commission on Radiological Protection** (ICRP, http://www.icrp.org/) that is responsible for recommendations on the protection quantities, as part of its wider work on general standards and systems for radiological protection.

However, the protection quantities, while being a good representation of detriment, are not readily measurable. Instead a set of **operational quantities** is used, which are intended to act as reasonable surrogates for the protection quantities, avoiding underestimation and too much overestimation. Although the operational quantities – like the protection quantities – are themselves not directly measurable, they possess a closer relationship with the field quantities (Figure 1.1), which are directly measurable. One of the important intentions behind the operational quantities is to provide conceptual guidance for designers and manufacturers of measuring devices, whether active or passive. It continues to be the task of the International Commission on Radiation Measurements and Units (ICRU, https://www.icru.org/) to monitor the performance of the operational quantities and to propose new ones as necessary.

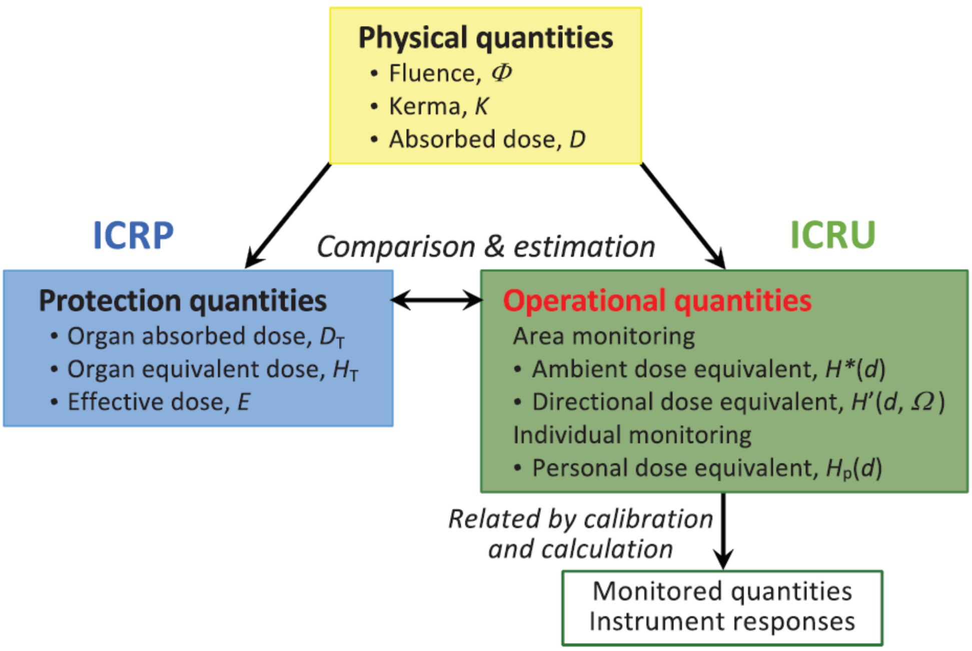

Figure 1.1. Relationship between the protection quantities defined in ICRP Publication 103 and the ICRU Report 39/51 operational quantities for use in radiological protection. (Taken from ICRU report 95.)

The final link in the chain of quantities is the set of conversion coefficients, based on calculation, that convert the physically-measurable **field quantities** to the operational quantities. The field quantities are typically air kerma, K_a, for photons, and fluence, Φ, for neutrons and electrons, and in a typical calibration procedure the measurement device will be exposed to a given air kerma or fluence, and the appropriate conversion coefficient applied to arrive at the corresponding value of the appropriate operational quantity. The conversion coefficients are calculated assuming well defined irradiation geometries that are easily reproduced in secondary standard calibration labs, using simplified phantoms to mimic the radiation receptor. Agreed conversion coefficients are arrived at by numerical calculations carried out and cross-checked by different institutes. The agreed conversion coefficients are then published in official publications (for example, ICRP Report 116 (2010), ICRU Report 60 (1998), and ISO 2019A-D). Conversion coefficients are required for the whole range of different radiations and different field configurations (energy and angle distributions) that might foreseeably be encountered by individuals.

1.3. The Current Operational Quantities

The current operational quantities have been in use since the 1980s, having been promulgated by ICRU in a series of three documents between 1985 and 1992 (ICRU 1985, ICRU 1988, ICRU 1992). Their introduction was widely welcomed, because they addressed significant problems with the previous quantities, which lacked additivity, and because they provided conceptual guidance to designers and manufacturers of dose measurement devices. The quantities for environmental and ambient monitoring are defined in a 30 cm diameter sphere of theoretical, tissue-equivalent material. They are:

- **Ambient Dose Equivalent**, $H^*(10)$, defined in terms of an expanded and aligned field and providing a good measure of the protection quantity Effective Dose when using survey instruments.
- **Directional Dose Equivalent**, $H'(0.07)$, defined in terms of an expanded field and providing a good measure of the protection quantity Equivalent Dose when using survey instruments.
- The operational quantity for individual monitoring is the **Personal Dose Equivalent**, $H_p(d)$, defined in the human body at a depth, d, in mm, appropriate to the protection quantity intended to be assessed. $d = 10$ for effective dose, $d = 0.3$ for equivalent dose to the eye lens, and $d = 0.07$ for equivalent dose to the skin. (For equivalent dose to the extremities, it is usual to measure $H_p(0.07)$ (International Organisation for Standardisation, 2015)).

1.4. New ICRU Operational Quantities

The current system of operational quantities has generally worked well, providing a significant improvement over the previous situation, and yielding good standards of protection in the majority of practical exposure situations. Owing to the long timescales required to change dosimetry systems (type testing and roll-out of new dosemeter designs, changes to software and – in some cases – changes to national requirements), it took some years for the current quantities to be adopted widely across Europe. They were included as a requirement in the relevant European Council directive of 1996 (Council for the European Communities 1996), and by 2003, 97% of individual monitoring services (IMS) were reporting $H_p(10)$ as a measure of effective dose (Stadtmann *et al*, 2004). In the latest such directive (Council for the European Communities, 2014 – see Article 13), the requirement is retained *via* reference to ICRP Publication 116 (International Commission on Radiological Protection 2010 – see section 2.3).

However, the current system has its drawbacks. Some of these have been present since the quantities were introduced, while others have become noticeable as the international system of radiation protection has evolved. These are discussed in more detail elsewhere in the present document, but they include the following.

- At diagnostic X-ray energies, roughly 30 – 100 keV, the current operational quantities have always substantially overestimated the protection quantities. Meanwhile, developments in interventional clinical procedures have meant that worker doses have been increasing in recent years, leading to a situation where compliance with regulations can be problematic.
- Whilst the current operational quantities work reasonably well in the radiation fields that are most frequently encountered, they do not work as well for other types and energies of radiations – for example around particle accelerators, such as proton therapy units. In space-crew environments the complexity is more severe, as not only are higher photon, neutron and electron energies encountered but also a wider range of radiations (e.g. protons, He ions, Fe ions, muons and pions). The opportunities for workers to receive doses in such environments are becoming more common.
- Conceptually, the relationships between field operational quantities and protection quantities are complicated, relying on both the ICRU sphere phantom and a calculated anthropomorphic phantom, on the radiation quality factor and on the radiation and tissue weighting factors.
- The kerma approximation, which considers all of the energy transferred in an interaction to be deposited at the point of interaction, leads to progressive divergence from the protection quantities as particle energies increase.

Furthermore, ICRP are known to be investigating a change to the protection quantities for protecting against harmful tissue reactions in the lens of the eye and in the skin. This change would see those protection quantities based on absorbed dose rather than, as now, equivalent dose. In defining the corresponding new operational quantities in terms of absorbed dose, ICRU are anticipating this change.

1.5. Changes in Approach

Accordingly, ICRU, in collaboration with ICRP, have developed new operational quantities (ICRU, 2020). See figure 1.2. The main philosophical change is that the operational quantities are now defined as the product of fluence at a point in space with conversion coefficients that are defined in the same anthropomorphic phantoms that are used to calculate the protection quantities. The differences between the current and new quantities are explored in more detail in Chapter 2.

In addition, the opportunity has been taken to extend the ranges of radiation energies and types for which conversion coefficients are available.

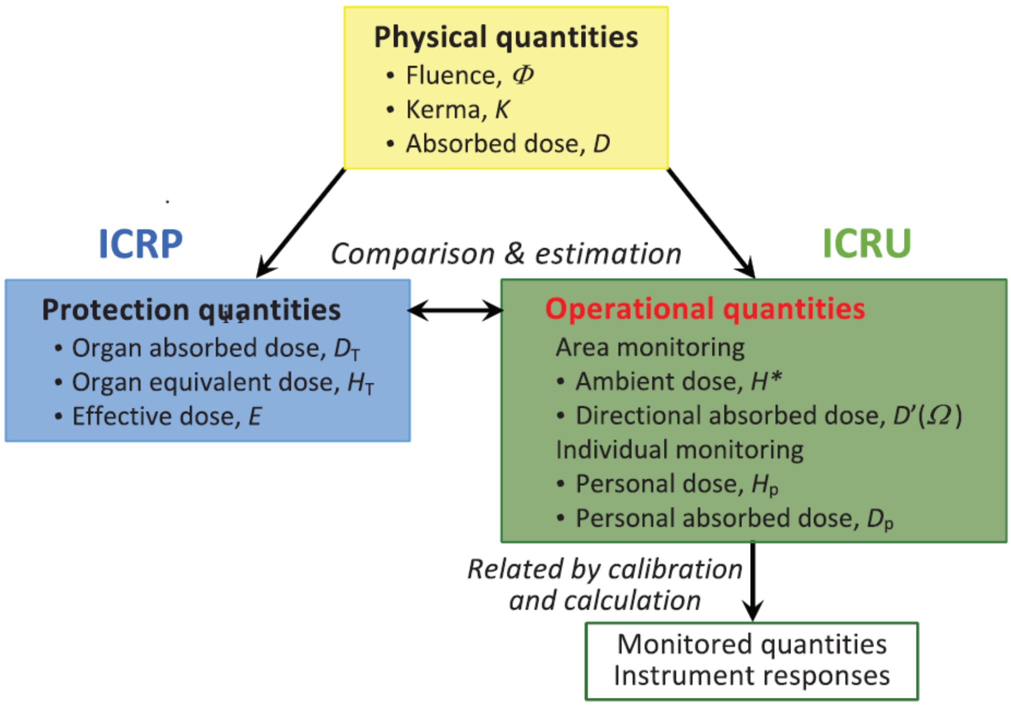

Figure 1.2. Relationship between the ICRP Publication 103 protection quantities and the new operational quantities recommended in ICRU Report 95 (ICRU, 2020). (Taken from that report.)

1.6. Scope of this Document

Given the importance of the proposed changes, in 2017-18 ICRP, on behalf of themselves and ICRU, carried out a wide-ranging consultation process. They received feedback from individual monitoring services, research scientists, metrology institutes and individual experts. These comments were considered, and changes made to later drafts of the proposals. They also included an explanation on some of the questions raised in the text.

This report aims to explore the consequences of introducing the proposed quantities. We look at the benefits and drawbacks, and identify areas where the proposed quantities can be introduced without significant changes to equipment or practice. We also point out the areas where changes will be needed and where costs will arise, although it is neither possible nor worthwhile to give here any more than a broad indication of what these costs might be.

In Chapter 2 we look in more detail at the differences between the existing and proposed operational quantities. Chapter 3 indicates the effect of changing to the new quantities, looking first at the underlying changes to fictitious "perfect" devices and then surveying the likely implications for a range of instrument and dosemeters. The survey is not exhaustive, but covers the most widely-used devices. At this stage we have chosen not to discuss other details, such as whether changes are needed to the physical phantoms used for calibration and type testing. Further chapters go on to explore the impact on radiation protection practices, on calibration and reference fields, on regulation/legislation (including dose registries etc.), and on existing standards such as those published by the International Standards Organisation (ISO) and International Electrotechnical

Commission (IEC). Chapter 7 summarises the conclusions and highlights the cost and resource implications.

1.7. "Pathfinder"

Whilst readers are encouraged to read the full report, and summaries can be found at the end of each chapter, different audiences are likely to find the certain chapters more relevant. In such a context we identified three levels for the different kind of readers (Table 1.1): mandatory (**M**), this is a fundamental chapter for your profession; suggested (S): you are invited to read it; optional (O): you can consider skipping it at a first reading and go to the summary of the chapter.

Table 1.1: Pathfinder to help the reader navigate this report

	1. Introduction and Scope	2. Main Differences with Existing Quantities/ Practice etc.	3. Impact on RP Practices	4. Impact on Dosemeter and Instrument Design	5. Impact on Calibration and Reference Fields, and International Standards	6. Impact on Regulation (including Dose Registries etc.)	7. Resource Impact (Economic, implications for training etc.)	8. Conclusions
Radiation protection experts/ medical and health physicists	**M**	**M**	**M**	S	O	**M**	S	**M**
Radiation employers/ radiation protection officers/ facility managers	**M**	S	**M**	O	O	S	**M**	**M**
Regulators/ policy makers/ accreditation bodies	**M**	S	**M**	S	S	**M**	**M**	**M**
Instrument/ device manufacturers	**M**	**M**	O	**M**	S	O	S	**M**
Metrology laboratories	**M**	**M**	O	S	**M**	O	S	**M**
Individual monitoring services	**M**	S	S	S	S	**M**	O	**M**

1.8. Disclaimer

EURADOS are very much aware that significant investigations into the new operational quantities will continue for some time. Whilst every effort has been made to ensure that our findings are based on the latest science, the most recent developments may not have been taken into consideration.

2. Main Differences between Operational Quantities used in current practice and new Operational Quantities

2.1 General aspects in the current operational quantity definitions: dose equivalent and the quality factor *Q*

2.1.1 Dose equivalent

During the 1980s and 1990s, ICRU introduced the current operational quantities *"for practical measurements, both for area and individual monitoring"* (ICRU 1985 report 39; ICRU 1993, report 51). They are based on the Dose Equivalent, *H*, defined as *"the product of the quality factor Q and the absorbed dose D"* (ICRU 1986, report 40). These quantities are specified at the "*same point of interest*". "*H is defined at a point in tissue"* (ICRP 1977, Report 26). The quality factor takes into account the differing biological effectiveness of the charged particles producing the absorbed does of different radiations.

$$H = \bar{Q}.D$$

The quality factor *Q* depends, in turn, on the unrestricted linear energy transfer *L* of charged particles in water. It is possible to calculate the *effective quality factor* $\bar{Q}$ as:

$$\bar{Q} = \frac{1}{D}\int Q(L)D(L)dL$$

Where the *D*(*L*)d*L* is the absorbed dose calculated for the LET interval (*L*, *L*+d*L*).

The use of *Q* values "*for particular types of radiation have been recommended by the ICRP*" (ICRP 1977, Report 26). They varied between 1 and 20 and were defined on the basis of the values of the unrestricted linear energy transfer *L* (keV/µm) in water. For *L* < 3.5 keV/µm, *Q* was assigned a value of 1, with this increasing to 20 at 175 keV/µm. Above 175 keV/µm *Q* was assigned a fixed value of 20. More recently (ICRP 1991, Report 60) *Q* was defined by ICRP employing generalized functions which peak at 30 for 100 keV/µm:

$$Q(L)\begin{cases} 1 \quad for \quad L \leq 10 \\ 0.32L - 2.2 \quad for \quad 10 < L < 100 \\ 300/\sqrt{L} \quad for \quad L \geq 100 \end{cases}$$

Concerning the values of *Q*, ICRU (ICRU 1992, Report 47) states that it would have been better to calculate *Q*, not based on linear energy transfer in water, but on the lineal energy, *y*, defined in a 1 µm diameter sphere of irradiated tissue (ICRU muscle). In particular, it is stated that *"while the definitions are given here in terms of D_L, it will be noted that in the measurements, one usually determines D_y, the distribution of the absorbed dose in y, so that approximations then have to be used to derive D_L"* (ICRU 1993, report 51).

Besides the matter of the definition of *Q*, it is clear that all the operational quantities, described as dose equivalent, refer to "*the type and energy of the radiation existing at that point and can therefore calculated on the basis of the fluence at the point*".

Although dose equivalent is defined at a point, which is a rigorous theoretical definition, point quantities are rarely of practical use. For example, when effective dose is calculated, it is based on the absorbed dose averaged over an organ or tissue, for which the quantity is realized using the ratio of the energy deposited in the organ or tissue, divided by its mass.

2.1.2 Current operational quantities for penetrating radiation

The next step recommended by ICRU is characterization of the field at that point, which could be in terms of fluence or air kerma depending on the monitoring quantity. Notwithstanding the fact that the aim of monitoring is the determination of the exposure of people, ICRU followed different approaches in the cases where the monitoring is performed through an area monitor or through a personal dosemeter.

In area monitoring for penetrating radiation, the ambient dose equivalent, $H^*(d)$, is used, and the phantom employed to simulate the presence of the human body is the ICRU sphere: a 30 cm diameter tissue-equivalent sphere with density 1 g cm^{-3} and mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen. Thus $H^*(d)$ requires, by its definition, the ICRU sphere. However, it is stated that "*In practical measurements, materials having elemental compositions and mass density somewhat different from those specified are often used and give adequate accuracy, although elemental equivalence may be necessary with mixed radiation field*". However, the ICRU sphere, as used in the definition of the quantity, is a "virtual" sphere, in that the quantity is defined as "receptor absent": the fluence at a point is expanded and aligned in a Monte Carlo simulation, and the quantity is then calculated at depth d on the axis opposing the direction of the field. This is done specifically to prevent underestimates of detriment or risk.

For individual monitoring the personal dose equivalent, $H_p(d)$, is used. It is defined as the dose equivalent at "*an appropriate depth d below a specified point on the body"*. ICRU state (ICRU 1992, Report 47) that "*the calibration of the dosimeter is generally performed under simplified conditions on an appropriate phantom;*" and "*While, at present, it may be convenient to make use of the extensive set of calculated conversion factors for the ICRU sphere, several other phantoms (sic) types are now in use for the calibrations* (of individual dosemeters). *The 30 cm × 30 cm × 15 cm depth PMMA phantom is recommended. Its mass is close to that of the ICRU sphere, and its backscatter characteristics are acceptably close to those of the human trunk for both photon and neutron irradiations*" [ICRP 1996, ICRU 1998]. For that reason, the conversion coefficients for whole body exposure have been calculated in a corresponding 30 cm × 30 cm × 15 cm slab made of ICRU tissue. $H_p(d)$, as distinct from $H^*(10)$, is "receptor present", so the attenuation of the radiation and scatter associated with the person/phantom are an inherent part of the definition.

The situation for the current operational quantities for penetrating radiation is given in Table 2.1.

Table 2.1: Summary of the definitions of ambient and personal dose equivalent

Ambient dose equivalent	**Personal dose equivalent**
$H^*(d)$ is defined in the ICRU sphere.	$H_p(d)$ is defined in a point in the receptor: the body or a phantom for calibration.
A "virtual" 30 cm radius ICRU sphere is used to simulate the presence of the body.	A 30 cm × 30 cm × 15 cm ICRU tissue slab is employed to simulate the body during calibration. As the quantity is defined in the person, for real dose measurements, the dosemeter has to be worn on the person to account for the radiation backscattered from the individual. The dose value depends on the size of the person. Therefore, to have well-defined conditions during calibration, the (individual) person is replaced by a standardized phantom.
Conversion factors are calculated in an ICRU sphere using Monte Carlo codes.	Conversion factors for calibration purposes only are calculated in an ICRU tissue slab using Monte Carlo codes.
$H^*(d)$ at a point is calculated by multiplying the free in air kerma or the fluence by the calculated conversion factor (for a given radiation and energy).	$H_p(d)$ at a point can be calculated by multiplying the free-in-air kerma, or fluence, by the conversion coefficient calculated at a depth d in ICRU 4-element soft tissue. For calculating calibration conversion coefficients the body is replaced by a phantom composed of ICRU 4-element soft tissue. For practical calibrations water-filled phantoms are used to simulate the whole body and head, whilst polymethyl methacrylate cylinders are used for the extremities. The presence of the phantom guarantees the condition of backscatter produced by the body on which the dosemeter is worn and attenuates the radiation field as it is transported to the reference point d mm behind the relevant face of the phantom.
ICRU sphere is required for the definition of $H^*(d)$ but it is a "virtual body" so no phantom should be used for the calibration of the monitor. The value of $H^*(d)$ does not depend on the dimensions of the real person in the radiation field.	The body or phantom is required for the definition. A slab (simulating the ICRU sphere / body) is used for the calculation of the conversion coefficients. A similar slab (but PMMA + water) has been defined by ISO for the calibration, simulating the backscatter radiation.

2.2 General aspects of the proposed operational quantity definitions: the conversion coefficient relating the dose to the effective dose.

For penetrating external exposures, ICRU are proposing two new quantities that are used for area monitoring and personal dosimetry respectively:

- The ambient dose, H^*, at a point in a radiation field is the product of the particle fluence at the point and the conversion coefficient, h^*_{Emax}, relating the particle fluence to the maximum value of the effective dose E_{max}.
- The personal dose, H_p, at a point on the body is the product of the particle fluence incident at that point and the conversion coefficient, h_p, relating particle fluence to the value of the effective dose, E.

The effective dose is calculated by ICRP with the updated radiation and tissue weighting factors (ICRP 2007, Report 103) and new adult reference computational phantoms (ICRP 2008, Report 110). The new conversion coefficients are no longer calculated using the *kerma approximation* (see 2.8), but by following the secondary charged particles generated by the impinging beam on the anthropomorphic models, which have been described in (ICRP 2010, Publication 116). ICRP Publication 116, however, does not contain the full set of energies and directions for all particle types, so the new ICRU proposals include many new calculations of effective dose: on the basis of these new conversion coefficients, the required h^*_{Emax} and h_p have been calculated by ICRU (Endo, RPD 2017).

Thus, from the point of view of radiation effects, the new quantity ambient dose directly relies on the radiation weighting factor w_R and no longer on Q. The w_R values and functions are based on the RBE (relative biological effectiveness) of different kinds of radiation and *"may therefore be seen as a factor representing radiation quality averaged over the different tissues and organs of the body"* (ICRP 2007, Report 103). In contrast to Q, the w_R values are independent of the field at the point at which they are employed: the w_R is set as the radiation enters the body, so changes to the energy and type of radiation that deposit energy at different points in the body are not explicitly accounted for. Whilst this may seem intrinsically unsatisfactory, when averaged over many particles incident on the body, it is a robust approach.

Thus, these new quantities are defined using absorbed dose and not dose equivalent, that strictly by definition is a quantity defined in a point. In fact, the w_R have been evaluated by ICRP following a mix of approaches. Detailed discussion is provided in ICRP 2007 describing how they were obtained using both data from RBE and the $Q(L)$ function for different types of radiation; for protons, for example, the $Q(L)$ has been employed.

Clearly, ambient dose, like ambient dose equivalent, is a point, receptor-free, quantity. It is simply calculated using the field at a point and the conversion coefficients. In practice, this is calculated using the maximum value for specific plane parallel fields with defined angles of incidence, or fields with defined isotropy.

Further sophistications are required for the definition of personal dose. It is defined as a point quantity, but uses a complex, extended phantom. It is defined as a receptor-present quantity. Consequently, its definition is necessarily quite complex. The "reference axis" for the calculations is on the central vertical axis of the reference phantom. No reference height is required because of the nature of the fields used for the conversion coefficient calculations. For the calculation of the reference conversion coefficients this is not a big issue, because the fields are plane parallel.

The definitions of the new operational quantities for penetrating radiation are summarized in Table 2.2.

Table 2.2: Summary of the definitions of ambient dose and personal dose

Ambient dose	**Personal dose**
H^* is defined as a product of a fluence or air kerma at a point and a conversion coefficient.	H_p is defined as a product of a fluence or air kerma at a point and a conversion coefficient.
Conversion coefficients are calculated in adult reference computational phantoms.	Conversion coefficients are calculated in adult reference computational phantoms.
No new phantom is required in the definition. No phantom is required for the calibration of the monitor.	No new phantom is required in the definition. A slab phantom, PMMA + water, should be used for the calibration, simulating the backscatter of human torso.

2.3 Comparison between the Ambient Dose Equivalent and Ambient Dose

The characteristics of the two quantities are compared in Table 2.3. Because the proposed quantity is not defined at a fixed depth and the secondary charged particles are followed, the maximum of the absorbed dose moves, as the primary radiation energy changes, from the “foreground” of the phantom to the “background” for a radiation impinging frontally. Because the conversion coefficients come directly from the limiting quantity, the reliability of the operational quantity is a good approximation of the corresponding radiation protection quantity is clearly guaranteed.

Table 2.3: Comparison between ambient dose equivalent and ambient dose

Ambient dose equivalent	**Ambient dose**
$H^*(d)$ is defined at a point in the radiation field.	H^* is defined at a point in the radiation field.
$H^*(d)$ is defined at depth d inside the ICRU sphere following alignment and expansion of the field.	H^* is the product of the fluence and the appropriate conversion coefficient.
d = 10 mm for penetrating radiations.	No fixed depth of a maximum (energy dependent).
Conversion coefficients have been calculated in ICRU sphere using the kerma approximation.	Conversion coefficients have been calculated considering the maximum of the E/ϕ for the reference adult voxel phantoms (IRCP 2009, ICRP 2010) at different incident geometries (AP, PA, LLAT, RLAT, ISO, SS-ISO, IS-ISO) with secondary charged particle transport. As a special case, charged particle equilibrium is assumed for calibration and the respective conversion coefficients are given in an Annex.
Conversion coefficients maximum energies: 10 MeV for photons 200 MeV for neutrons	Conversion coefficients maximum energies: 10 GeV for photons, neutrons, protons, negative muons, positive muons, negative pions, positive pions, ^{4}He nuclei

For the proposed quantity there is no need for a fictitious material in which to define the quantity itself. But reference adult phantoms are needed for the calculation of the conversion coefficients. Ambient dose is defined at a point, even if the conversion coefficients are calculated for a whole individual.

2.4 Comparison between the "Directional Dose Equivalent", and "Directional Absorbed Dose to the Lens of the Eye" and "Directional Absorbed Dose in the Local Skin"

The characteristics of the three quantities are compared in Table 2.4. A key change in the new quantities is the definition in terms of grays rather than sieverts. Like ambient dose equivalent, directional dose equivalent requires the ICRU sphere for its definition. The difference between the two quantities is the lack of alignment in the definition of directional dose equivalent, so the conversion coefficient tends to fall with increasing angle of incidence.

For the new quantity Directional Absorbed Dose to the Lens of the Eye, D'_{lens}, no new phantom is required in the definition because the conversion coefficients are calculated on the basis of the values published in the ICRP Publication 116 (ICRP 2010) and based on Behrens's detailed model of the eye (Behrens, Dietze and Zankl, 2010). Two full sets of conversion coefficients (full transport and kerma-approximation) have been published to provide the data needed for D'_{lens} (Behrens 2017). They are calculated for a whole-body irradiation using a simplified phantom. This quantity is for area monitoring, and is hence receptor-free, so the eye model and whole-body phantom are "virtual", and only used in the calculation of the conversion coefficients.

For the dose in the local skin three new phantoms are introduced consisting of a ICRU 4-element tissue (ρ = 1.0 g cm^{-3}) covered by a 2 mm outer layer of skin of density 1.09 g cm^{-3} of elemental composition given in ICRP Publication 89 (ICRP, 2002). These are intended to cover the whole body, extremity (wrist or ankle) and finger exposures:

- Exposure of the trunk: at the centre of the front surface of a slab phantom of dimensions 300 mm × 300 mm × 148 mm of ICRU 4-element tissue (ρ = 1.0 g cm^{-3}), the front surface of which is covered with 2 mm of skin (ρ = 1.09 g cm^{-3}) (ICRP, 2009), of elemental composition given in ICRP Publication 89 (2002). The absorbed dose is averaged over the volume of a right circular cylinder between depths of 50 µm and 100 µm and a cross-sectional area of 1 cm^2 for angles, φ, from 0° (AP) to 75° in 15° steps.
- Exposure of the extremity: at the half-length of the cylindrical surface of a 69 mm diameter 300 mm length pillar phantom of ICRU 4-element tissue (ρ = 1.11 g cm^{-3} to take account of internal structure), the cylindrical surface of which is covered with 2 mm of skin. The absorbed dose is averaged over the volume between the radii 36.4 mm and 36.45 mm with a circle of area 1 cm^2 projected onto the upper and lower cylindrical surfaces perpendicular to the radii, for angles, φ, from 0° to 180° in 15° steps and for rotational geometry.
- Exposure of the finger: at the half-length of the cylindrical surface of a 15 mm diameter 300 mm length rod of ICRU 4-element tissue density (ρ = 1.11 g cm^{-3}), the cylindrical surface of which is covered with 2 mm of skin. The absorbed dose is averaged over the volume between the radii 9.4 mm and 9.45 mm of a circle of area 1 cm^2 projected onto the upper and lower cylindrical surfaces perpendicular to the radii, for angles, φ, from 0° to 180° in 15° steps and rotational geometry.

Table 2.4: Comparison between directional dose equivalent and directional dose

Directional dose equivalent for skin and lens of the eye	**Directional absorbed dose in the lens of the eye**	**Directional absorbed dose in the local skin**
$H'(d,\Omega)$ is defined at a point in the radiation field.	$D'_{lens}(\Omega)$ is defined at a point in the radiation field.	$D'_{local\ skin}(\Omega)$ is defined at a point in the radiation field.
$H'(d,\Omega)$ is defined in the virtual ICRU sphere at the depth d, on a radius in a specific direction, Ω.	$D'_{lens}(\Omega)$ is the product of the particle fluence at that point, $\Phi(\Omega)$, and the conversion coefficient, $d'_{lens}(\Omega)$, relating particle fluence to the value of absorbed dose in the lens of the eye.	$D'_{lens}(\Omega)$ is the product of the particle fluence at that point, $\Phi(\Omega)$, and the conversion coefficient, $d'_{local\ skin}(\Omega)$, relating particle fluence to the value of absorbed dose in local skin.
ICRU sphere is required	No phantom is required, although a virtual eye model and whole-body phantom were used in the computation of the conversion coefficients.	A new phantom is required ICRU + skin tissue.
Conversion coefficients maximum energies: 10 MeV for photons and electrons	Conversion coefficients maximum energies: 50 MeV for photons, electrons and positrons	Conversion coefficients maximum energies: 50 MeV for photons, electrons, neutrons, positrons 10 MeV for α-particles

2.5 Comparison between the Personal Dose Equivalent and Personal Dose

The characteristics of the two quantities are given in Table 2.5.

The personal dose does not require any new phantom because it is defined through the effective dose coefficients calculated in the ICRP Publication 116 (ICRP 2010) employing the voxel reference models. That implies that there is not a specific reference depth but that the maximum of the dose follows the deposition of the charged particles in the human body for the different energies and angles of incidence. The conversion coefficients for the personal dose are calculated for the whole body.

Table 2.5: Comparison between ambient dose equivalent and ambient dose

Personal dose equivalent	**Personal dose**
$H_p(d)$ is defined below a specific point in the body or on a calibration phantom.	H_p is defined at a point on the body.
$H_p(d)$ is defined in ICRU 4-element soft tissue.	H_p is the product of the fluence and the appropriate conversion coefficient.
d = 10 mm for penetrating radiations d = 0.07 mm for the skin d = 3 mm for the eye	No fixed depth of a maximum (energy dependent).
Conversion coefficients have been calculated in ICRU slab in kerma approximation.	Conversion coefficients have been calculated considering the E/ϕ for the reference adult voxel phantoms at different incident angles with secondary charged particle transport.
Conversion coefficients maximum energies: 10 MeV for photons and electrons 200 MeV for neutrons	Conversion coefficients maximum energies: 1 GeV for photons, neutrons, electrons, positrons, protons, negative muons, positive muons, negative pions, positive pions, ^{4}He ions

2.5.1 Receptor present versus receptor absent

There are many changes in the definitions of the operational quantities in ICRU Report 95 (ICRU 2020), but one aspect that gets relatively little attention is the issue of whether a quantity is “receptor present” or “receptor absent”. The difference is never given a strict definition in earlier ICRU Reports, but, broadly speaking, it is intended that quantities that are used for measurements using instruments are receptor absent and those for personal dosimetry are receptor present. All of the current and proposed operational quantities are defined at a point, but it is considered necessary for the person or phantom to perturb the field for personal dosimetry, because it provides both backscatter for radiation arriving from the front, and attenuation of radiation arriving from the back. Hence those quantities are “receptor present”. The receptor present/absent nature of the current operational quantities follows naturally from the definition.

$H_p(d)$ is defined at a point in soft tissue (person) and is primarily intended for exposures from the “front” (< 90°). The point is located at a depth d below the location of the personal dosemeter. For an exposure from the front, the dose equivalent at that point includes backscattered radiation that is returning from deeper in the phantom, which will also emerge from the phantom and affect the response of the dosemeter. Consequently, calibrations need to take place on a standardized phantom instead of a person so that the dosemeter can respond appropriately for the location at which the quantity is defined. For H_p, the quantity is defined at a point, but the relevant effective dose is distributed throughout a pair of virtual reference voxel phantoms. The whole-body dose backscatter to depth d is almost irrelevant because there is not likely to be an organ specified for effective dose at that point. But the real receptor is needed to account for the influence of the backscatter on the dosemeter reading.

Although a receptor is needed for both quantities, there is a conceptual difference. While $H_p(10)$ is defined in the person, resulting in different $H_p(10)$ values for different people, H_p is defined in the reference standard humans only – therefore, the H_p value will be the same for any person.

In ICRU Report 95, the proposed quantities are defined as receptor absent or present according to their usage for instruments or personal dosemeters. But there remains the question of whether this follows naturally from their definitions, or not. It is evident that the receptors for the personal dose conversion coefficients and for calibration are different, with the former being the reference voxel phantoms and the latter being a slab of tissue equivalent material. The "receptor" for personal dose is clearly providing the backscatter, but it is not providing the attenuation. For example, for irradiation from 180°, the field is not attenuated as strongly in reaching the critical organs as it is to reach a depth of 10 mm below the front face of the slab.

The issues of receptor present and receptor absent are somewhat less clear for personal dose, because measurements are made on a receptor, the person or the calibration phantom, while that receptor is not present in the calculation of the quantity, which is simply based on the fluence at that point, as though the person were not there. In an entirely theoretical sense, this may be uncomfortable but acceptable. Similarly, in the calibration laboratory, for which the fields are intended to be as close to plane parallel as can be achieved, this is not a significant issue. In a workplace, however, where there is radiation coming from many directions, the fields are often divergent. The concept of this being a receptor present quantity, but based on free-in-air, plane parallel irradiation conversion coefficients, is a different receptor present concept from that previously recommended.

2.6 Comparison between the Personal Dose Equivalent (used for eye lens and skin) and Personal Absorbed Dose in the Lens of the Eye and Personal Absorbed Dose in the Local Skin

The characteristics of the three quantities are compared in the Table 2.6.

Table 2.6: Comparison between personal dose equivalent and personal absorbed dose

Personal dose equivalent	Personal Absorbed Dose in the Lens of the Eye	Personal Absorbed Dose in the Local Skin
$H_p(d)$ is defined below a specific point on the body/phantom.	$D_{p\ lens}$ is defined at a point on the head (or the body).	$D_{p\ local\ skin}$ is defined at a point on the skin
$H_p(d)$ is defined in soft tissue.	$D_{p\ lens}$ is the product of the particle fluence incident at that point, Φ, and the conversion coefficient, $d_{p\ lens}$, relating particle fluence to the value of absorbed dose in the lens of the eye.	$D_{p\ local\ skin}$ is defined as the product of the particle fluence incident on the body or extremities, Φ, and the conversion coefficient, $d_{p\ local\ skin}$, relating particle fluence to the value of absorbed dose in local skin.
d = 0.07 mm for the skin d = 3 mm for the eye	No phantom is required, although a virtual eye model and whole-body phantom were used in the computation of the conversion coefficients.	Three new phantoms are required ICRU core + ICRP skin tissue layer: TRUNK, EXTREMITIES and FINGERS
Conversion coefficients have been calculated in ICRU slab using the kerma approximation.	Numerically identical conversion coefficients are employed for the directional absorbed dose in the lens of the eye. For a given direction Ω the maximum between right and left lens is taken. In the workplace the quantity is the integration of directional dose equivalent over all angles.	For the trunk numerically identical conversion coefficients are employed for the directional absorbed dose in the local skin.
Conversion coefficients maximum energies: 1 MeV for photons (0.07 mm only) 10 MeV for electrons	Conversion coefficients maximum energies: 50 MeV for photons 50 MeV for electrons	Conversion coefficients maximum energies: 50 MeV for photons 50 MeV for electrons

The personal absorbed dose in the lens of the eye, $D_{p\ lens}$, employs the conversion coefficients reported in ICRP Publication 116 (ICRP 2010), based on the Behrens and Dietze detailed phantom of the eye, itself based on the anatomic details according to Charles and Brown (Charles and Brown, 1975). Two eye models are embedded in a simple anthropomorphic phantom, with the higher value of the two being used for $D_{p\ lens}$.

For personal dose in the local skin, three phantoms are introduced. Inside each phantom there is an outer layer of 2 mm skin of density 1.09 g cm^{-3} (ICRP, 2009) with the elemental composition given in ICRP Publication 89 (2002).

- for the trunk, a slab of ICRU 4-element tissue (ρ = 1.0 g cm^{-3}) with dimensions 300 mm x 300 mm x 150 mm, in which the dose is averaged over the volume of a right circular cylinder between the depths of 50 µm and 100 µm and a cross-sectional area of 1 cm^2 below the centre of the front surface;
- for the extremities, a pillar of ICRU 4-element tissue (with density in this instance taken to be equal to 1.11 g cm^{-3}) with dimensions 73 mm diameter and 300 mm length, in which the dose is averaged over a curved target cylinder with a cross-sectional area of 1 cm^2 and thickness 50 µm, embedded 50 µm under the cylinder mantle and situated at half-length of the pillar;
- for the finger, a rod of ICRU 4-element tissue (with density in this instance taken to be equal to 1.11 g cm^{-3}) with dimensions 19 mm diameter and 300 mm length, in which the dose is averaged over a curved target cylinder with a cross-sectional area 1 cm^2 and thickness 50 µm, embedded 50 µm under the cylinder mantle and situated at half-length of the rod.

2.7 Discussion and comments on some specific points

2.7.1 Angles in the definition of conversion coefficients and dosemeter irradiation

Two planes are used in the definition of personal dose (ICRU 2020), one in the horizontal plane and the other in the vertical plane. It is known that equal positive and negative rotations do not produce identical effective dose because of the asymmetry of the internal organs, so in the definition both positive and negative rotations are used to produce an average conversion coefficient. The data in ICRU Report 95 are for 0°, avg(±15°), avg(±30°), avg(±45°), avg(±60°), avg(±75°) ,avg(±90°), 180°, ROT, ISO, SS-ISO and IS-ISO. Whilst it is not stated, it is presumed that these also angles apply to both horizontal and vertical rotations: for example, a downward or upward 45° rotation must have the same conversion coefficient as the avg(±45°), even though the conversion coefficients are ultimately only described in terms of the horizontal rotation.

One very satisfactory aspect of the new quantities is the absence of a discontinuity around 90° that is implied for personal dose equivalent when calculated on a slab phantom. The use of the anthropomorphic phantom gets around that problem. It is also good to have a 180° conversion coefficient, which was missing from ICRU Report 57, but there are relatively few conversion coefficients for reverse angles. The definition of $H_p(10)$ meant that reverse angles had very low conversion coefficients unless the radiation was highly penetrating. This is no longer true, because the radiation that is incident from behind can reach radiosensitive organs much more effectively than it could when it needed to penetrate at least 14 cm of ICRU tissue. It is unclear whether this definition might require more personal dosemeters to be worn, because in scattered workplace fields, the personal dose may be much higher than can be measured by a dosemeter on the front of the body. The absence of conversion coefficients for angles between 90° and 180° could prove an issue, because a dosemeter mounted on the front of the body will still need to respond to radiation incident from those directions, because for all penetrating radiation H_p, unlike $H_p(10)$, will have a significant conversion coefficient for reverse angles of incidence.

For personal dosemeter calibrations the reference point for the irradiations is at a point in the dosemeter or on the front face of the calibration phantom (ICRU Report 95). This sits somewhat uncomfortably with the definition of the personal dose with reference to the central axis of the reference phantoms. For plane parallel calibration fields this is probably not a problem, but the "receptor present" nature of this new quantity is less obviously a direct implication of the definition than it was for personal dose equivalent.

2.7.2 Absorbed doses versus dose equivalent

"Directional Absorbed Dose to the Lens of the Eye" and "Directional Absorbed Dose in the Local Skin": a key change in the new quantities is the definition in terms of grays rather than sieverts, which is justified because the quantities are being used to limit the potential for tissue reactions rather than stochastic effects. In the current system of radiation protection having an annual skin dose limit of 0.5 Sv seems peculiar until it is realized that this equates to an equivalent dose to the skin of 5 mSv, once the tissue weighting factor for the skin is accounted for. The justification is less clear for the lens of the eye, which now has a 20 mSv annual dose limit because the evidence for cataracts being a tissue reaction with a threshold is less clear (Ainsbury *et al*, 2009, ICRP, 2012, Hamada and Fujimichi 2014).

Because they are generally considered tissue reactions, considering the possible radiation effects on the lens of the eye and on the skin, the definition of the operational quantity as absorbed dose and not dose equivalent is more correct, from a theoretical point of view. As already stated, this may be less certain for high LET radiations, which still require an RBE weighting for tissue reactions, though it is recognized that this is different from that applied for stochastic effects in ICRP Publication 118 (ICRP, 2012).

Considering "Personal dose in the Lens of the Eye", instead of $H_p(3)$, means employing absorbed dose rather than dose equivalent and this is logical for particles that have $w_R > 1$, because the weighting factor for higher LET is probably not appropriate. But in some cases this should be taken with caution, for example, it is true that neutron $H_p(3)$ (Gualdrini, Ferrari and Tanner, 2013) probably overestimates detriment. However, the new quantity probably overcompensates and underestimates the risk for high LET exposures because there is now no RBE weighting.

2.7.3 The future

ICRP updated the tissue weighting factors in Publications 60 and 103, and the radiation weighting factors in ICRP 103. The phantom used for the calculations of effective dose also became more complex in the transition from ICRP Publication 60 to Publication 103. None of these changes required changes to the operational quantities, though the change to the quality factor in ICRP Publication 60 did. It can be anticipated that the next major ICRP review of radiation protection, which will trigger the next revision of legislation, will include updated values for tissue weighting factors and also new radiation weighting factors.

More recently, ICRP have published: effective dose conversion coefficients calculated for age dependent phantoms (ICRP, 2020 B, Publication 144); paediatric phantoms (ICRP, 2020 A, Publication 143); and mesh type phantoms (ICRP, 2020 C, Publication 145). All of these indicate a direction of travel toward more realistic representation of the individual and also might indicate the rejection of a single male and female phantom pair to represent all adults.

These developments in the knowledge of the effects of different radiations on the body and the better mathematical descriptions of the body point towards ever developing effective dose definitions. A consequence of having operational quantities based on effective dose, is that a full new set of conversion coefficients is likely to be required every time ICRP updates its definition of effective dose.

2.8 Full-Transport and Kerma-Approximation Conversion Coefficients

The conversion coefficients used for the ICRU Report 95 operational quantities are calculated using full secondary charged particle transport, whereas those for photons and neutrons in ICRU Report 57 and ICRP Publication 74 were calculated using the kerma approximation, whereby the absorbed dose is calculated from the energy released at a point rather than the energy deposited at that point. Whilst this is a significant change, it is not a change of quantity definition. Instead it is more a reflection of the improved Monte Carlo codes and computing power now available. The conversion coefficients published in ICRU Report 57 and ICRP Publication 74 were calculated by EURADOS Working Group 6, *Computational Dosimetry*, using the best methods then available. At that time, codes were far more limited than now. In particular, the ability to run coupled calculations for photons/electrons or neutrons/charged particles was only beginning to be developed. Additionally, this simplification of the method was forced by deficiencies in the electron transport in terms of its accuracy and by CPU requirements: it was not a mistake.

In practice, the use of the kerma approximation will only cause problems when secondary charged particle equilibrium (CPE) cannot be assumed. It is a problem when the materials in the model vary over the ranges of the secondary particles: a clear example of this is the use of the kerma approximation, in a vacuum to calculate $H_p(d)$ or $H^*(d)$, for energies where the ranges of the secondary particles generated exceed d (Pellicioni, 2000). It is also a problem for small structures that feature large local variations in density or material composition, such as are found within the bones of the body. However, the problems in part derive from the calculation in a vacuum, because in practice secondary charged particles are generated in the source, the air and the shielding materials.

CPE, however, is not simply a phenomenon that has to be tolerated – it is a standardisation tool. Calibration laboratories normally aim to ensure CPE, as one of the standardised conditions. Meanwhile, CPE exists in many routine workplace fields. Thus CPE exists:

- when calibrating dosemeters and instruments.
- when type-testing dosemeters and instruments.
- in most routine use situations.

Because the full secondary charged particle transport conversion coefficients are defined in a vacuum, their use brings some practical problems. When calibrating dosemeters in the laboratory, for example, the presence of air makes it highly impractical to ensure a pure photon field, with no electron component. This issue is significant for photons, especially for the skin and eye dose quantities.

ICRU have recognized this problem and have also published conversion coefficients for photons that use the kerma approximation, but only up to 50 MeV as opposed to the 10 GeV used with full secondary particle transport[1]. In practice the kerma approximation conversion coefficients cover almost all workplaces, the exceptions being cosmic ray and accelerator fields, though even there the conditions are likely to be far from those presumed in the calculation of the non-CPE coefficients. This is because the shielding (and air) will provide some secondary particle build-up. It can be anticipated that ISO and IEC will recommend these kerma approximation conversion coefficients for

[1] ICRU 95, Appendix A5: "Operational Quantities for Photons of Energies up to 50 MeV in Fields With Charged-Particle Equilibrium"

reference calibration fields and instrument/dosemeter calibrations for most workplace dosimetry. Some conversion coefficients for beta and photon reference radiation fields, according ISO 6980-1 (Behrens, 2021) and ISO 4037-1 (Behrens and Otto, 2020), are already published in peer-reviewed papers. As will be seen in Chapter 3, for skin and eye lens dosimetry, the two sets of conversion coefficients diverge significantly at higher photon energies.

Because the kerma approximation is valid in CPE conditions, and because CPE conditions exist in the situations listed above, it will be the kerma-approximation conversion coefficients that are used in the vast majority of applications involving photons. Practical applications for the full-transport, non-CPE conversion coefficients will be limited.

2.9 Radiation fields in space and at aircraft altitudes

Radiation protection measures in space and aircraft altitudes differ substantially from the typical measures for exposures on earth, since the radiation fields are very complex and extend to very high energies and hence have no analogues on Earth.

Astronaut protection is not yet embedded in the radiation protection system of ICRP. No operational quantities for assessment of dose in the body were defined for space activities by ICRU or ICRP. Nevertheless, measurements performed with waist dosimeter serve as input for the astronaut exposure records. Measurements of absorbed dose in TLD-700, and LET spectra of heavy ions and neutrons in PADC (CR39®), allow dose equivalent estimates to be made by applying the quality factor as defined in ICRP60. These can be used as conservative estimates of effective dose in the astronaut exposure records. Phantom measurements support this procedure as it was shown that such measurements overestimate the effective dose measured in depth dose studies in human phantoms by about 15%.

Civil aircrew protection is fully embedded in the ICRP system (e.g. ICRP, 2016 - ICRP132). At airflight altitudes, "the use of one properly validated calculation program is considered sufficient for assessment of [effective] dose for aircraft crew and passengers". Work is therefore concentrated on the development of such programs, which are regularly benchmarked against measurements of ambient dose equivalent $H^*(10)$, which itself provides a conservative estimate of effective dose. Monitors inside aircraft are not recommended since it is very difficult continuously cover the whole radiation field spectrum and the instruments to do this are very bulky. Therefore, such measures are impractical.

2.9.1 Radiation fields in space

The use of operational dose quantities for area monitoring of external exposures, and for assessing effective dose, is not applicable for space dosimetry, because many different types of particles are involved with very high energies (ICRP, 2013). Instead, the measurement and determination of particle fluence and its distribution in energy and direction are more important and provide a better basis for an assessment of doses.

ICRP 123 (ICRP, 2013) describes the exposure situations in space and the terms of, and methods to assess, the radiation exposure of astronauts. It also provides conversion coefficients for particle fluences to absorbed doses in organs and tissues, and mean quality factors for protons, neutrons, charged pions, alpha particles, and heavy ions up to Z = 28.

Exposure situations in space can vary widely, with the radiation field depending strongly on whether the location of interest is: inside the Earth's magnetosphere or outside; inside the spacecraft or in habitations on planetary surfaces; or outside the spacecraft or outside such habitations, with the astronauts just equipped with a space suit. It should be noted that all these exposures also vary according to the activity of the sun, which results in a change of energy spectra of primary galactic cosmic rays (GCR) and can cause unpredictable strong disturbances by the sudden injection of solar particles into the heliosphere. In addition, mass distributions inside spacecraft will also change, thereby changing attenuation and scatter of the primary field and the production of the secondary particles, in turn modifying the radiation exposure of organs and tissues.

In general, space dosimetry has to deal with three radiation sources (Reitz, 2008):

- Galactic Cosmic Rays (GCR), which are incident isotropically and consist of 98% baryons and 2% electrons. The baryonic component comprises mostly protons (about 85%), alpha particles (about 14%) and about 1% of heavier ions. The particle energies range from a few eV up to 10^{20} eV. GCRs are hard to shield, as the production of secondary radiation (due to nucleus-nucleus interactions) compensates for their absorption, and can even increase the radiation exposure depending on the shielding materials and thicknesses used in typical spacecraft. Exposure rates can reach up to 1 mGy per day.
- Solar Cosmic Radiation (SCR) is released in Solar particle events (SPE), which are of the most concern for human spaceflight. They can have energies up to several GeV and consist mostly of protons, although there are also small amounts of heavy ions in varying proportions. Exposures may reach several Gy of skin dose, if astronauts are exposed in space suits only. Spacecraft need to be equipped with thick shelters of up to 40 $g.cm^{-2}$ to reduce the exposure significantly. The angle of incidence of SCR on spacecraft can be considered close to isotropic for large events, due to scatter in the interplanetary medium.
- Trapped radiation (TR) consists of charged particles produced in interactions of GCRs or SCRs with the molecules of the Earth's atmosphere, through neutron decay, or injected into the Earth's magnetosphere by the sun, which have been captured by the Earth's magnetic field. This source is an important part of the exposure in low earth orbit (LEO) e.g. on the International Space Station (ISS). TR electrons with energies up to 7 MeV may cause considerable skin and eye exposures in extravehicular activities, but they are completely absent inside the ISS. Conversely, TR protons of up to 600 MeV, with a peak energy of around 90 MeV, contribute considerably to the exposure inside the spacecraft. The angle of incidence of TR is peaked in a given direction, rather than being isotropic.

ICRP 123 states (para 131): in radiation fields in space, with its large spectrum of different types of particles of very high energies, the definition of $H^*(10)$ seems inappropriate (ICRP, 2013). This, and the measurement of particle fluences using dose conversion coefficients, is in line with the new ICRU report. However, the simple concept of considering the differences in radiobiological effectiveness by radiation weighting factors, w_R, (e.g. a constant radiation weighting factor of 20 for all heavy ions of all energies), is not appropriate for dosimetry in space. Instead, the quality factor Q is applied for the definition of the quantity 'dose equivalent' in an organ or tissue of the human body. The basis for risk assessments for the astronauts is the dose equivalent in organs and tissues of adult males and females, H_T, Q_M and H_T, Q_F, which are based on mean absorbed doses, D_T , and mean quality factors in the corresponding organs or tissues, Q_T., The protection quantity is defined according to ICRP 123, para 122 and 123.

If a quality factor is defined by a function $Q(Z,E)$, a mean Q_T-value can be calculated by (terms as defined in ICRP 123):

$$Q_{\mathrm{T}} = \frac{1}{m_{\mathrm{T}} D_{\mathrm{T}}} \int_{m_{\mathrm{T}}} (\sum_{Z} \int_{E} Q(Z,E) D_{E}(Z,E) \mathrm{d}E \mathrm{d}m$$

Or alternatively

$$Q_{\mathrm{T}} = \frac{1}{m_{\mathrm{T}} D_{\mathrm{T}}} \int_{m_{\mathrm{T}}} (\sum_{Z} \int_{L} Q(Z,L) D_{L}(Z,L) \mathrm{d}L \mathrm{d}m$$

Similarly to equivalent dose in an organ or tissue, H_{T}, the value of dose equivalent in an organ or tissue is defined for organs and tissues in females and males by:

$$H_{\mathrm{T,Q}}^{\mathrm{F}} = Q_{\mathrm{T}}^{\mathrm{F}} D_{\mathrm{T}}^{\mathrm{F}} \qquad H_{\mathrm{T,Q}}^{\mathrm{M}} = Q_{\mathrm{T}}^{\mathrm{M}} D_{\mathrm{T}}^{\mathrm{M}}$$

The monitors that are used serve as instruments for recording the environmental radiation field outside or inside a spacecraft, as control of the environment and hence for warning in cases of sudden increases of radiation exposure levels due to solar energetic particle (SEP) events. They measure particle types, fluences and microdosimetric quantities and absorbed doses. This is achieved using detectors in assemblies of various sizes, both integral and differential (with respect to time, or LET, or energy, or direction, as appropriate). These data are then used as input or validation for calculations of doses in the human body. Data from an Astronaut dosimeter worn at the waist are usually used to normalize to model calculations.

2.9.2 Radiation fields at Aviation Altitudes

The radiation field in the atmosphere at aviation altitudes is quite different from that in space (Reitz *et al*, 1993). It is shaped mainly by Galactic Cosmic Rays (GCR) and Solar Cosmic radiation (SCR). The peak of GCR energy distribution is at a few hundred MeV to 1 GeV per nucleon, depending on solar magnetic activity, and it follows a power function for higher energies. The fluence rate is fairly constant with time (but is modulated by solar activity in low energies) and is isotropic. Energies of SCR are usually lower than 100 MeV/nucleon but sometimes reach even 10 GeV/nucleon. Due to irregularities of magnetic field and shocks in the interplanetary medium, the usual spectrum of solar energetic particles varies from event to event and even change throughout the event duration. Intensity of solar particles at low energies is several orders of magnitude greater than that of GCR. During some events, even at several hundred MeV, fluence rate of solar protons can still be much higher than those of galactic origin. Solar events very often show high anisotropy especially in their initial phase.

Galactic Cosmic Rays (GCR) and Solar Cosmic radiation (SCR) interact with the atomic nuclei of atmospheric constituents, producing a cascade of interactions and secondary reaction products. As a result, the radiation field in the atmosphere is very complex with various particle types (the most important from radiation protection point of view are neutrons (see Figure 2.1), protons, electrons, gamma rays, muons and pions) and energies spanning over several orders of magnitude. All these particles contribute to cosmic radiation exposure in the atmosphere. Unlike the space radiation environment, the contribution from heavy ions (or fragments) is not significant. The exposure decreases in intensity with depth in the atmosphere from higher aviation altitudes (about 15 km) down to sea level. The relative contribution to that exposure also changes. At ground level, the greatest dose is due to muons; at cruising altitudes (from ~8 km to ~15 km) about 50% of dose is due to neutrons only, while above 25 km – 30 km protons start to dominate (see Figure 2.1).

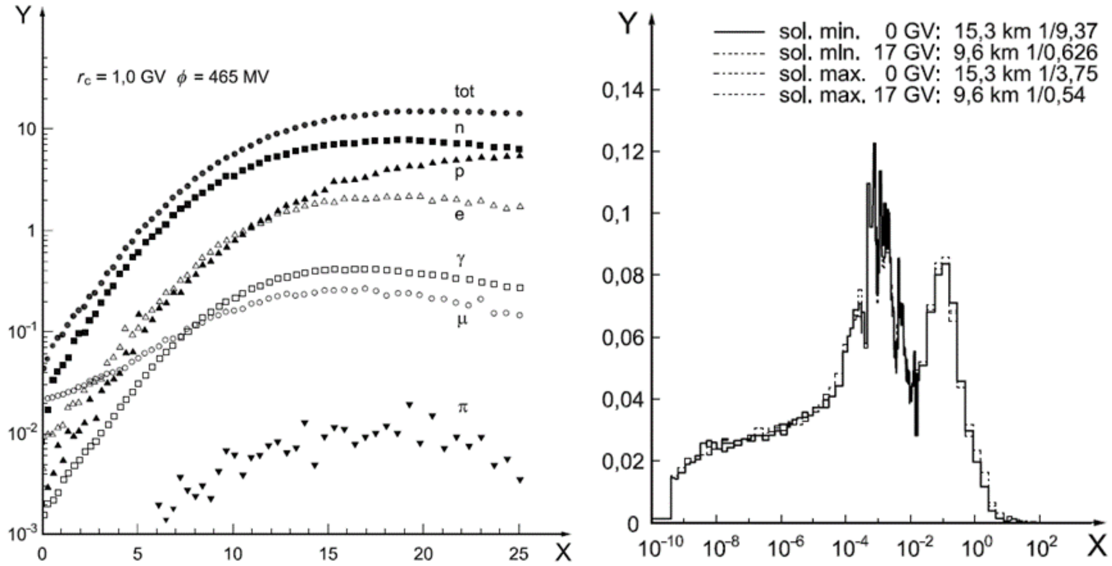

Figure 2.1 Left: Calculated ambient dose equivalent rates (Y axis in μSv/h) as a function of standard barometric altitude (X axis in km) for high latitudes (at 1 GV cut-off) at solar minimum (solar deceleration potential of 465 MV) for various atmospheric cosmic radiation component particles (ISO, 2020 A – 2020 B – ICO 20785 series]. Right: Normalized energy distribution of neutron fluence rate (Y axis in /cm^2/s/GeV) as a function energy (X axis in GeV) (ICO 2020 A-D)

Following recommendations of the ICRP (formulated in its Publication 60 and confirmed in Publication 103), the EU introduced a Basic Safety Standard Directive in which exposure to natural sources of ionizing radiation (including cosmic radiation) is considered as occupational. The directive calls for action to be taken if the annual exposure of aircraft crew is liable to be more than 1 mSv (effective dose). In fact, aircraft crew are one of the most highly exposed occupational groups.

The BSS identifies protective measures to limit the exposure; the first one is to assess the exposure. The preferred approach for the assessment of doses to aircraft crew, where necessary, is to calculate the effective dose. Most commonly, it is done by the use of validated cosmic ray models combined with a Monte Carlo (MC) transport model. It is widely accepted that such calculations should be validated by measurements. The protection quantity, effective dose, is not directly measurable; currently, for measurements, the operational quantity ambient dose equivalent is used. $H^*(10)$ was designed to be conservative with respect to effective dose, but before the IRCP 103 recommendations (which, among others, lowered radiation weighting factor w_R for protons from 5 to 2, and changed the w_R function for neutrons) this was not the case in atmospheric radiation fields (Latocha *et al*, 2006). However, with the current ICRP 103 recommendations the situation is improved. It has been shown in model calculations that $H^*(10)$ can now be considered a conservative estimate for the effective dose in aviation (Meier and Matthiä, 2019). A wider study on comparing of ICRP103 effective dose calculated by various codes used for radiation protection of aircraft crew is currently being conducted by EURADOS WG11.

2.10 Conclusions of the chapter

1. Slab versus anthropomorphic models: the current quantities are defined in a point in a body. Because individual people differ, for calibration purposes the sets of conversion coefficients are calculated at a point (at a certain depth) in a slab of fictitious ICRU soft tissue. ISO 4037-3 implemented the water slab phantom of same the dimensions. The proposed quantities are defined employing the ICRP conversion coefficients calculated through reference voxel models (of a standard human), or in the ICRP detailed model of the standardized head. The only exception is the proposed operational quantities for the skin for which new phantoms, made of ICRU tissue and skin tissue, are defined, not being possible using the skin of the ICRP voxel models (that has a thickness corresponding to the voxel dimension).
2. Dose equivalent versus absorbed dose for tissue reactions. The current definition uses a dose equivalent (i.e. related to stochastic effects) for specific tissue/organs (eye and skin) that uses the absorbed dose multiplied by some RBE factor. The proposed ones are defined through an absorbed dose that is the correct quantity to be associated with tissue reactions (through some "quality factor").
3. In contrast to the current operational quantities $H(3)$ and $H_p(3)$, for the new proposed quantities the conversion coefficients to be used, calculated in the ICRP eye detailed model, are the same. The same happens with the skin related proposed operational quantities.
4. There are extensions of particle types and energy ranges in the new ICRU proposal, indeed all the calculations have been done following the charged particles. That means that, at higher energies, there is no misplacement of the maximum of energy deposition produced instead when the kerma approximation is used in the radiation transport.
5. For spacecraft activities no operational quantities are specified, so no impact can be identified by the new ICRU recommendation. Recommendations of ICRP 123 should be applied. Exposure assessments should be done by calculations in combination with particle and energy spectra measurements for model verification.
6. At aircraft altitudes, assessments of effective doses are in practice done by model calculations. The models are verified with measurements of $H^*(10)$ because this operational quantity is considered conservative (especially after ICRP103 recommendations). Measurements of $H^*(10)$ are most commonly conducted with TEPCs – these instruments, when appropriately calibrated, can measure that quantity quite well when compared with other measurement set-ups. A significant problem arises because the new ICRU recommendations effectively preclude such measurements (see Chapter 3). As currently used, TEPCs provide the best estimate of $H^*(10)$, which in turn provides a reasonable estimate of E.
7. For almost all photon applications, including calibration and measurements, the set of conversion coefficients in ICRU 95 Appendix 5, calculated using the kerma approximation method, must be used.

3. Impact on Dosemeter and Instrument Design

3.1 Chapter Introduction

The response of an ideal dosemeter or instrument exactly matches the energy- and angle-dependent characteristics of the dose quantity that it is intended to measure, for the radiation fields that define its intended scope of application. Of course, no real device can ever perform this task perfectly. Nevertheless, designers of dosemeters and instruments invest considerable time optimising their performance, within reasonable and unavoidable constraints such as cost, ease of manufacture, non-tissue equivalence of the sensitive material, physical size, shape and mass, etc.

Even hypothetical instruments and dosemeters whose response characteristics are ideal for the existing operational quantities will need design changes in order to provide optimal responses to the new quantities. These changes will be dictated by the changes to the values of the conversion coefficients, which are used to relate the responses to the primary physical dose quantities. The changes can be quantified for a particular radiation exposure at a given energy or angle by considering the ratio of the old and new conversion coefficients for that field, though it is necessary in this analysis to also consider the ratios for the fields that are used during routine calibration.

In reality, however, it is more complicated to interpret whether the impacts on current designs of dosemeters and instruments are positive or negative. This is due to the imperfect responses of real dosemeters and instruments, leading to the possibility that a change in the value of the conversion coefficient for a particular radiation exposure at a given energy or angle could result either in a fortunate mitigation of a current over- or under-response for that exposure, or in an unfortunate exacerbation of a current over- or under-response. So, whilst some general trends can be predicted, the impact of the changes to the dose quantities will be both instrument- and field-specific, and will hence need to be judged on a case-by-case basis.

The purpose of the current chapter is to consider how existing technologies might cope with the changes to the operational dose quantities. A comparison of the values of the old and new conversion coefficients will first be provided, followed by a discussion of how the energy- and angle-dependences of the response characteristics of typical dosemeters and instruments might generally be affected. Consideration will then be given of what modifications might be made to existing designs of instrument, or to the ways in which they are calibrated or used, in order for them to better match the performances required by the new quantities.

The current chapter is associated with two caveats, however. Firstly, the new ICRU report (ICRU, 2020) contains data for particle types and energies that were not included in previous recommendations (ICRU, 1998, Report 57). Partly this is because, at the time of publication of the earlier work, the computational capability which is required to evaluate the values of the conversion coefficients was not available. This evaluation becomes increasingly demanding at higher energies when the ranges of secondary charged particles become longer. But also, the new work reflects a shift in the requirements of the radiological protection community over time, such as those due to increased interest in accelerator or medical fields. These new fields will not be discussed in great depth in the current chapter, however, because it aims to consider the impact on existing designs of instruments and dosemeters, which were not necessarily intended for use in such fields and therefore not originally optimized for performance within them.

Secondly, the current comparisons are not exhaustive and will not consider how every dosemeter or instrument in current usage might be impacted: doing so would be extremely difficult, and would also make the analysis unhelpfully long. Instead the discussion will be in general terms, and where examples are provided the focus will be just on the commonest types of dosemeter and instruments and their representative calibration characteristics, and on the types of workplace environment in which they are most frequently employed.

3.2 Comparison of conversion coefficients

A number of comparisons between the old and new operational dose quantities are provided and discussed in the ICRU report (ICRU, 2020). Some of those figures are reproduced here in their original form, without any replotting or amendment. This is partly to avoid unnecessary duplication of effort, but also because direct copying is assumed to aid clarity for readers wishing to cross-reference the present and ICRU documents directly. Due credit to the creators of the original figures in the ICRU report is acknowledged implicitly.

3.2.1 Preface: Photon conversion coefficients in ICRU 95

The recommendations in ICRU Report 95 for conversion coefficients for photon dosimetry are, arguably, somewhat confusing. In the earlier ICRU Report 57, all of the conversion coefficients that are provided for photons were calculated under the conditions of secondary charged-particle equilibrium (CPE), i.e. by assuming the validity of the kerma approximation throughout (see 2.8 above). In ICRU Report 95, however, two sets of photon conversion coefficients are provided: Appendices A1 to A4 list data calculated without CPE in place, whilst Appendix A5 lists data calculated under CPE conditions. Each appendix provides conversions to its dose quantities from both fluence and air kerma, the latter of which is a technical inconsistency in A1 to A4 because it was obviously calculated under CPE.

Chapter 4 of ICRU Report 95 is dedicated to the conversion coefficients, and is where the appendices are introduced, *viz*.:

> "*All calculations reported are performed with full transport of generated particles. Depending on the quantity and the particle type, at high energy the radiation fields in the scoring regions of the phantom are not in equilibrium. Personal dosimeters and area monitoring instruments for photons are customarily calibrated in a setup where charged-particle equilibrium is established. For this purpose, additional conversion coefficients for photons are calculated in the kerma approximation, which delivers numerical results close to the situation of charged-particle equilibrium. The resulting sets of conversion coefficients are given in Appendix A, by quantity, particle type, energy, and angle of incidence.*"

Appendices A1 to A4 are then individually cited and discussed in the remaining sub-sections of this conversion coefficients chapter. These non-CPE data are also compared in Chapter 4 against the values for the analogous dose quantities published in ICRU 57, with the aim of demonstrating the advantages of the proposed quantities over the older conversion coefficients (which were calculated under CPE conditions), especially for very high- or low-energy photon sources, for example. Moreover, in all of those figures for photons in that chapter, the captions state explicitly that the non-CPE data that are being used are the values that are recommended (e.g. Figure 4.2: "*Comparison of incident photons of conversion coefficients from fluence to personal dose equivalent at 10 mm depth,* h_p*(*10,0°*), shown as a ratio to the recommended values of* h_p(0°)").

Appendix A5 is not mentioned explicitly in ICRU 95 Chapter 4; indeed, the only direct reference to it in the main body of the report is sub-section 5.3.3, which comprises the statement:

"*In routine procedures for the calibrations of area monitoring instruments and personal dosimeters in photon fields, conditions approximating full charged-particle equilibrium are used. Therefore, an additional set of conversion coefficients for photons, calculated using the kerma approximation to approximate charged-particle equilibrium, is provided (see Appendix A.5) for photon energies up to 50 MeV.*

If there is insufficient air between the photon source and the monitoring instrument or personal dosimeter or area monitoring instrument, charged-particle equilibrium is obtained by placing in front of the monitoring instrument or personal dosimeter or area monitoring instrument a build-up plate made from PMMA with a thickness depending on the photon energy. The small attenuation in the build-up plate must be corrected for in the calculation of the rate of the operational quantity at the calibration point (ISO 4037-3:2019). This procedure guarantees reproducible calibration conditions independent of the design and collimation of the calibration source employed because it eliminates electron contamination in the photon beam as well as creating charged-particle equilibrium. It delivers conservative calibration coefficients in photon fields where charged-particle equilibrium is not attained, but can require separate monitoring of the contaminant electrons which could dominate the field."

Similarly, the introduction to Appendix A5 simply states:

"The calibration of area monitoring instruments and personal dosimeters for photon radiation to measure ambient dose, personal dose, directional and personal absorbed dose in the lens of the eye and local skin is performed routinely in air with sufficient material in front of the instrument to provide full charged-particle equilibrium at the point of test (Section 6.2). The calculations of conversion coefficients given here use the kerma-approximation method to approximate absorbed dose when there is charged-particle equilibrium."

The CPE conversion coefficients are not otherwise described further in ICRU 95, with the majority of the discussions instead focussing on the non-CPE data. Moreover, and unlike for the non-CPE data (Appendices A1 to A4), the CPE conversion coefficients for photons in Appendix A5 are not compared against the analogous ICRU 57 datasets, nor discussions provided on their relative merits.

This differing emphasis within the report therefore suggests that the non-CPE data in Appendices A1 to A4 are considered 'primary' by ICRU, with the CPE data in A5 then a subsidiary dataset that find application under certain specialized circumstances, namely during routine calibration of photon dosemeters and instruments within metrology laboratories. Indeed, there is even some indication that ICRU mean for the new quantities to be exclusively non-CPE by definition, and that actually it would be a misconception to compare a CPE-quantity, such as $H_p(10)$ for example, with a non-CPE quantity, such as H_p. But, that would infer that the conversion coefficients given in Appendix A5, such as 'air kerma to H_p' or 'fluence to H_p' for example, must really be to a dose quantity other than H_p, by definition, if these subsidiary data were calculated with CPE enforced. Either way, the above implications could lead to some confusion within the dosimetry community.

In fact, and contrary to the apparent intentions, it is likely that the CPE data will be used almost universally for photons, with the non-CPE data employed only for highly specialized applications. This is for several reasons. Firstly, for photons it is highly impractical to establish reliable non-CPE conditions in calibration laboratories. There is no choice but to use CPE conditions for calibrations and type testing, and dosemeters and instruments need to be designed accordingly. If not, and they were instead designed to have a response optimized in terms of non-CPE conversion coefficients, for example, those theoretical performances could differ greatly from their measured performances when subsequent type-test calibrations are carried-out under conditions of CPE.

Secondly, CPE conditions typically exist in the vast majority of workplace photon fields, especially for whole-body doses (where $H_p(10)$ or H_p, or $H^*(10)$ or H^* are appropriate) or eye doses (where $H_p(3)$ or $D_{p\ lens}$ are appropriate), with exceptions most likely to occur only when very high energy components are present. Again, if individuals working in such CPE fields wore dosemeters intended to respond in terms of a non-CPE quantity, their performances would differ from those expected under routine calibration; analogous arguments may of course be made for dose survey instruments.

One solution that might naïvely be proposed would be to design and calibrate dosemeters under both CPE and non-CPE conditions in tandem; but that would obviously be impractical, not least because the latter calibrations would need to be performed in a vacuum to match the circumstances in which the non-CPE conversion coefficients are defined and calculated. It could similarly be suggested that it be left to the discretion of dosimetry services and instrument manufacturers to decide which version of the conversion coefficients they might choose to apply; but that would clearly lead to significant confusion for them, their customers, and dose registries, for example.

An alternative view could be that the description of the data in Appendix A5 is simply misleading, and that ICRU do in fact intend for the CPE conversion coefficients to be used in every circumstance (design, calibration, use, etc.) that relates to dosemeters and instruments monitoring occupational photon doses. Indeed, and excluding some workplaces with very high energy photon components, a dosemeter designed and calibrated in terms of CPE is more likely to over-estimate than under-estimate the dose to the individual if worn in non-CPE conditions. This inherently conservative nature of the CPE conversion coefficients is obviously closer to the ‘spirit’ of what an operational dose quantity is invented to achieve. But, that interpretation would lead inevitably to the question: what is the purpose of the non-CPE conversion coefficients for photons? If they are not ever intended for use with personal dosemeters or ambient monitors, which has historically been considered the principal motivation for defining an operational dose quantity, when does ICRU anticipate or recommend their use? Such envisaged applications do not seem to be discussed in any detail in the ICRU report, despite the non-CPE data being presented as having apparent primacy.

In an attempt to answer that question, it might be suggested that the non-CPE conversion coefficients could find applications in novel or future endeavours; this might include ‘online dosimetry’, for example, where computational approaches are used to estimate individual doses in real time (as described later in Section 3.5.4 of this report). In such cases, however, given the free availability of reference voxel / mesh anthropomorphic phantoms and the increasing ability of mainstream general-purpose Monte Carlo codes (e.g. MCNP, GEANT, PHITS, etc.) to incorporate them, as well as the extensive conversion coefficient datasets already published in ICRP 116, it would be better just to calculate effective dose instead. Similarly, perhaps ICRU envisage that the non-CPE data may find use in some specialized computational research projects, though they do not elaborate on the possible nature of such applications; but again, in those cases, experienced Monte Carlo modellers may instead prefer to directly calculate doses in situ for their own bespoke applications, rather than relying on limited tables of generic conversion coefficient data. Alternatively, it might be proposed that the non-CPE conversion coefficients could be used in designing special dosemeters for use just in high-energy environments, such as the fields around accelerators or from cosmic rays, where the presumed CPE conditions naturally start to break down. However, calibration conditions would still be a significant issue for such an endeavour, as discussed more in Section 5 below. In addition, operational quantities are not generally used for aviation or space dosimetry applications (see Section 3.4 below), which further undermines this argument.

Accordingly, while the non-CPE conversion coefficients have initially been adopted as the primary datasets for analysis throughout the remainder of Section 3.2 and Section 3.3, the later Section 3.5.1.2 considers the impact of instead using CPE (kerma-approximation) data.

In section 3.2.1, comparisons of old and new operational dose quantities intended for personal monitoring are shown and discussed. A similar analysis for area monitoring dose quantities is provided in section 3.2.2.

3.2.2 Impact for personal dosimetry

Figure 3.1 shows the angle-dependent ratios between the 'old' quantity personal dose equivalent at a depth of 0.07 mm and the 'new' quantity personal absorbed dose in local skin, for photons and electrons. It is clear that a dosemeter that currently responds well to $H_p(0.07)$ will over-estimate $D_{p\ local\ skin}$ for photons with energies above ~300 keV and perform poorly in general for electrons with energies below ~150 keV. For photons, the divergence at higher energies is caused by the assumption of secondary charged particle equilibrium (kerma approximation) used for the calculation of the $H_p(0.07)$ conversion coefficients, but not used for $D_{p\ local\ skin}$. For electrons, the large positive and negative divergences at the lowest energies are probably the outcome of two competing factors. At the lowest energy, the difference is probably due to the conversion coefficient data being calculated using different scoring volumes bounded at different depths: the dose is averaged over 50 to 100 μm depths for $D_{p\ local\ skin}$, but this range is unspecified for $H_p(0.07)$ in ICRU 57, though presumably begins a little deeper than 50 μm because the dataset[2] is truncated at ~70 keV for $H'(0.07)$ (at 0°, cf. ICRU, 1984). Conversely, the dominant factor for electrons at 100 keV is probably the effect of the tissue being slightly more attenuating overall for the new quantity: ICRP skin of density 1.09 g cm^{-3} for $D_{p\ local\ skin}$, but ICRU 4-element tissue of density 1.00 g cm^{-3} for $H_p(0.07)$.

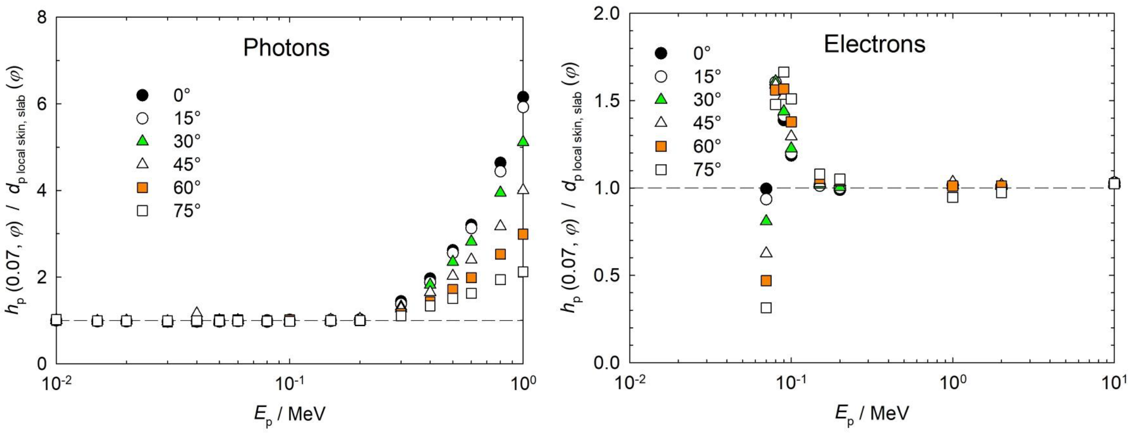

Figure 3.1 Ratios of $h_p(0.07)$ to $d_{p\ local\ skin,\ slab}$ as a function of energy and angle, for photons and electrons.

Figure 3.2 shows the angle-dependent ratios between the quantity personal dose equivalent at a depth of 3 mm and personal absorbed dose in the lens of the eye, for photons and electrons. It is

[2] Conversion coefficient data for $H_p(0.07)$ are not tabulated in ICRU 57 for electrons, but may reasonably be presumed to be numerically equal to $H'(0.07)$ at 0°.

clear that a dosemeter that currently responds well to $H_p(3)$ will over-estimate $D_{p\ lens}$ for photons with energies above ~2 MeV and perform poorly in general for photons with energies below ~100 keV, with more than a factor of two difference even at small angles of incidence. Again, the divergence at higher energies is caused by the assumption of secondary charged particle equilibrium (kerma approximation) used in the calculation of the $H_p(3)$ conversion coefficients, but not used for $D_{p\ lens}$. The dosemeter will generally perform poorly for electrons, with its response a strong function of energy and angle.

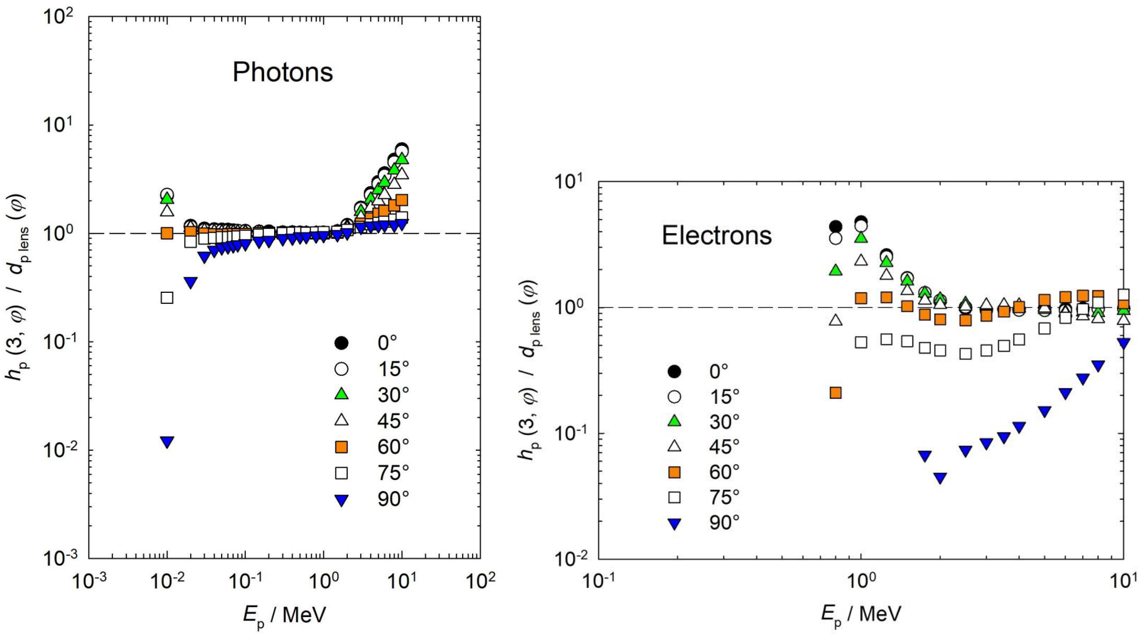

Figure 3.2 Ratios of $h_p(3)$ to $d_{p\ lens}$ as a function of angle, for photons and electrons.

Figure 3.3 shows the angle-dependent ratios between the quantity personal dose equivalent at a depth of 10 mm and personal dose, for photons, electrons and neutrons. It is clear that a dosemeter that currently responds well to $H_p(10)$ will over-estimate H_p for photons at all but extremely low energies, but the magnitude of this is fairly small (<few tens of percent) at energies above ~100 keV. The dosemeter would exhibit energy and angle dependent under- and over-responses of a factor of a few across its entire energy range for neutrons. For electrons, a large over-response would generally be exhibited at energies above ~3 MeV, with a very large under-response seen at low energies. The explanation for this latter under-response is that only electrons with energies greater than ~2 MeV have ranges that are sufficiently long to be able to contribute to $H_p(10)$, but all electrons, whatever their energy, will deposit energy in the voxel phantoms used to calculate personal dose so will always contribute to H_p. In principle, this implies that any dosemeter intended to monitor personal dose in fields containing electrons must be able to respond down to arbitrarily low energies, which is a difficult requirement to fulfil.

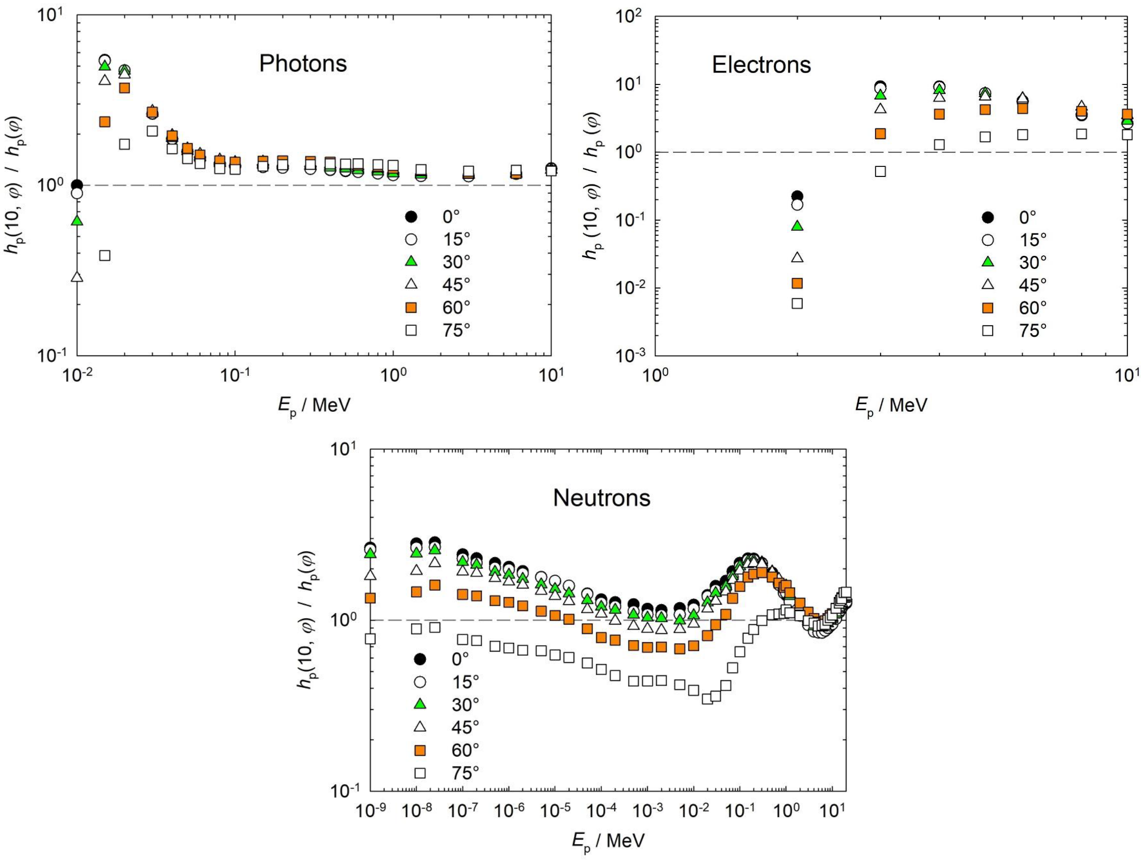

Figure 3.3 Ratios of $h_p(10)$ to h_p as a function of energy and angle, for photons, electrons and neutrons.

3.2.3 Impact for area monitoring

Figure 3.4 shows the angle-dependent ratios between the quantity directional dose equivalent at a depth of 0.07 mm and directional absorbed dose in local skin, for photons and electrons. It is clear that an instrument that currently responds well to $H'(0.07)$ will over-estimate $D'_{\text{local skin}}$ for photons with energies above ~300 keV. The divergence at higher energies is caused by the assumption of secondary charged particle equilibrium (kerma approximation) used in the calculation of the $H'(0.07)$ conversion coefficients, but not used for $D'_{\text{p local skin}}$. For electrons, an instrument that currently responds well to $H'(0.07)$ will all also respond well to $D'_{\text{local skin}}$ at energies above ~150 keV, but below this energy it will respond poorly. For electrons, the large positive and negative divergences at the lowest energies are probably the outcome of two competing factors, identical to those described in section 3.2.1. At the lowest energy, the difference is probably due to the conversion coefficient data being calculated using different scoring volumes bounded at different depths: the dose is averaged over 50 to 100 μm depths for $D'_{\text{local skin}}$, but this range is unspecified for $H'(0.07)$ in ICRU 57, though presumably begins a little deeper than 50 μm because the dataset is truncated at ~70 keV (at 0°, cf. ICRU, 1984). Conversely, the dominant factor for electrons at 100 keV is probably the effect of the tissue being slightly more attenuating overall for the new quantity: ICRP skin of density 1.09 g cm^{-3} for $D'_{\text{local skin}}$, but ICRU 4-element tissue of density 1.00 g cm^{-3} for $H'(0.07)$.

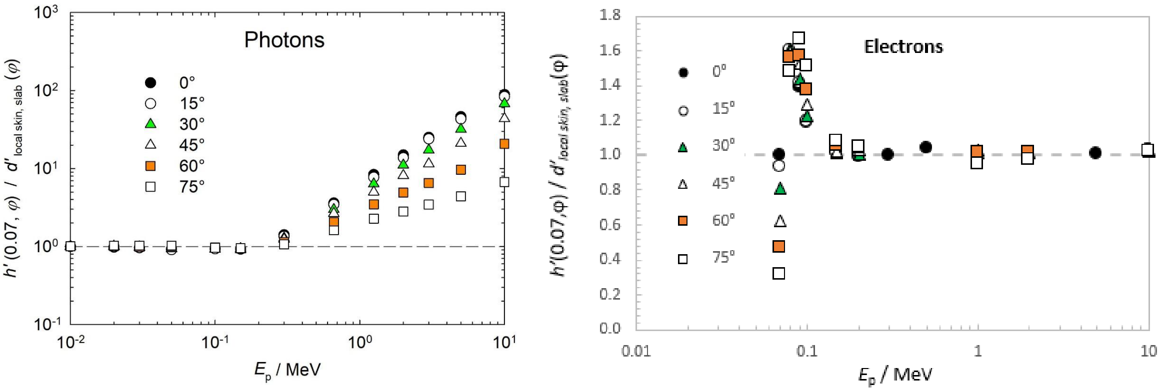

Figure 3.4 Ratios of $h'(0.07)$ to $d'_{\text{local skin, slab}}$ as a function of energy and angle, for photons and electrons.

Figure 3.5 shows the angle-dependent ratios between the quantity directional dose equivalent at a depth of 3 mm and directional absorbed dose in the lens of the eye, for photons and electrons; the data-points at 0.8 MeV for electrons correct a presumed typographical error in ICRU 57, where an energy of 0.08 MeV is instead listed. It is clear that an instrument that currently responds well to $H'(3)$ will over-estimate D'_{lens} for photons with energies above ~2 MeV and perform poorly in general for photons with energies below ~100 keV. As before, the divergence at higher energies is caused by the assumption of secondary charged particle equilibrium (kerma approximation) used in the calculation of the $H'(3)$ conversion coefficients, but not used for D'_{lens}. The instrument will generally perform poorly for electrons, with its response a strong function of energy and angle.

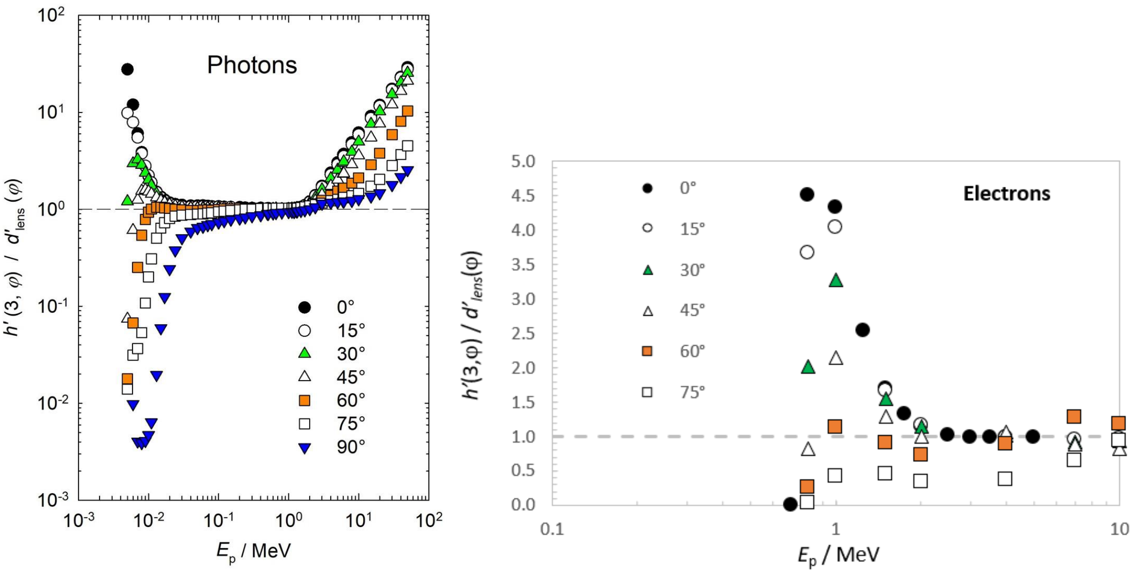

Figure 3.5 Ratios of $h'(3)$ to d'_{lens} as a function of energy and angle, for photons and electrons.

Figure 3.6 shows the ratios between the quantity ambient dose equivalent at a depth of 10 mm and ambient dose, for photons, electrons and neutrons. It is clear that an instrument that currently responds well to $H^*(10)$ will respond well to H^* for photons in the intermediate energy range, but over-estimate at energies below ~100 keV and increasingly under-estimate at increasing energies above ~3 MeV. For neutrons, the instrument would over-respond at energies below ~2 MeV and between ~10 and ~40 MeV, but under-respond between ~2 and ~10 MeV and at energies above ~40 MeV. For electrons, the instrument would over-respond at energies between ~3 and ~30 MeV, but under-respond outside of this range, with divergences of several orders of magnitude exhibited at the lowest energies.

Data for other types of radiations, including protons, can be found in ICRU report 95 (ICRU, 2021).

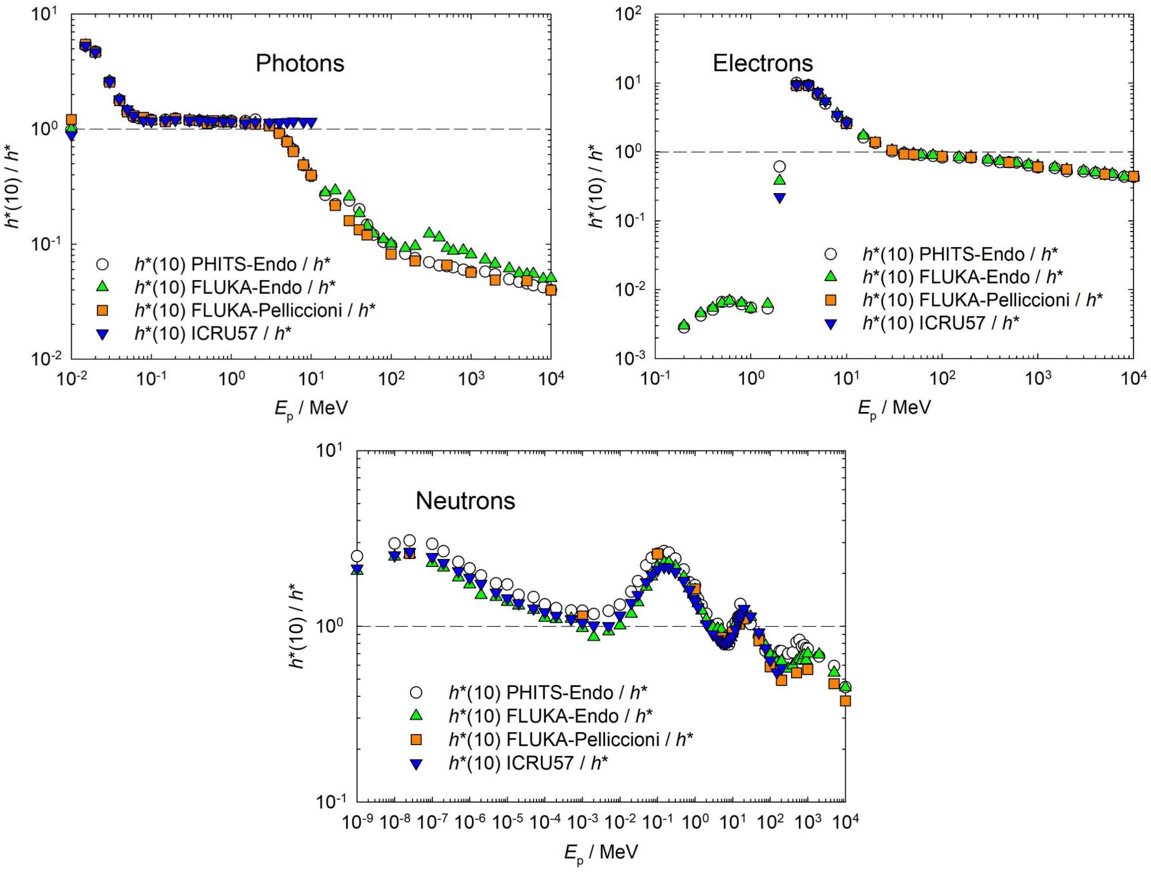

Figure 3.6 Ratios of $h^*(10)$ to h^*, for photons, electrons and neutrons.

3.3 Impact for real dosemeters and instruments

The data plotted in section 3.2 above show the differences in the values of the conversion coefficients for the old and new operational dose quantities. However, when predicting the impact of the updated dose quantities on the estimates of risk obtained from real dosemeters and instruments, it is necessary to factor in their non-ideal response characteristics. These departures from a flat response may be caused by a number of factors, and may be common to all dosemeters or instruments of a given type, or else unique to a specific design. An example of the former could be caused by non-tissue equivalence of the detecting medium, due to different materials having different K-edge characteristics and hence different energy-dependent dose deposition signatures for a given radiation type, which could lead to departures from a flat response characteristic within a predictable and well-defined energy interval. A second example could be where the definition of the dose quantity makes it extremely difficult to measure accurately with a single device across the whole energy range of interest, given restrictions on available technology and requirements such as cost, ease of use, and portability. Conversely, an example of the latter type could be a restricted design of instrument or dosemeter, where for instance a relatively inexpensive device may perhaps be produced and used if only indicative dose estimates are required from it or if only a limited energy range needs to be focussed upon, with comparatively large uncertainties then considered acceptable during its routine use on the assumption that other ALARA procedures are being followed.

The consequences are that real dosemeters and instruments typically exhibit energy- and angle-dependences of response. For a given device, there may be some energy and angle ranges for which it over-responds and some ranges for which it under-responds, to greater or lesser extents. The impacts of the new dose quantities will therefore be non-trivial for real devices, with the possibility that the various divergences anticipated from Section 3.2 could either decrease or increase the under- or over-response of a given device at a given energy and angle, depending on whether the 'direction' of the conversion coefficient divergence opposes or matches, respectively, the direction of the device's non-flatness of response. It is therefore conceivable that the response of a given device might be improved at some energies and angles but worsened at others, with no general cancelling-out of these two effects necessarily expected overall.

A number of authors have already considered the impacts of the new quantities for a limited selection of dosemeters and instruments (Eakins *et al*, 2018; Tanner *et al*, 2018; Eakins *et al*, 2019; Otto, 2019a; Pozzi *et al*, 2019; Ekendahl *et al*, 2020; Hoedlmoser *et al*, 2020; Caresana *et al*, 2021; Polo *et al,* 2021). Some of those key results are reproduced and discussed here, with some additional data also presented. Clearly, however, this discussion cannot be exhaustive; the examples given are therefore included just to illustrate general points and to demonstrate the typical levels of impact that might be anticipated.

3.3.1 Personal dosemeters

3.3.1.1 Extremity dosemeters

Figure 3.7 shows the effect of the new quantities on a ring dosemeter that uses BeO as an optically stimulated luminescence (OSL) sensitive element, for both photon and beta exposures; responses are normalized to the $D_{\mathrm{p\ local\ skin\ Rod}}$ or $H_{\mathrm{p}}(0.07)$ response (as appropriate) to the ISO Narrow Series N-300 X-ray field. The implication is that the change to the quantities would leave the shape of the response relatively unchanged below ~200 keV, which is arguably the most important region for extremity dosimetry, but the chosen normalization would lead to a consistent under-response in that range. A large over-response would be caused at higher energies, which compounds the normalization. The divergence is probably caused by the assumption of kerma conditions for the $H_{\mathrm{p}}(0.07)$ conversion coefficients but not for $D_{\mathrm{p\ local\ skin\ Rod}}$, as discussed later.

Figure 3.7 also shows the effect of the new quantities on a finger-stall dosemeter that uses LiF:Mg,Cu,P as a thermally stimulated luminescence (TLD) sensitive element, for monoenergetic photon and electron exposures at normal incidence; responses are normalized to the $D_{\mathrm{p\ local\ skin\ Rod}}$ or $H_{\mathrm{p}}(0.07)$ response (as appropriate) to the ^{137}Cs field. For electrons, the assumption is made that $H_{\mathrm{p}}(0.07)$ and $H'(0.07)$ are numerically equivalent at normal incidence, with conversion coefficients for the latter used to generate the data in Figure 3.7, because data for the former are not provided explicitly in ICRU 57. The implication is that the change to the quantities would leave the shape of the electron response relatively unchanged, and the shape of the photon response relatively unchanged below ~200 keV, similarly to the case for the BeO dosemeter, but the routine calibration to ^{137}Cs would lead to large under-responses for betas and lower-energy photons and a severe energy-dependence overall.

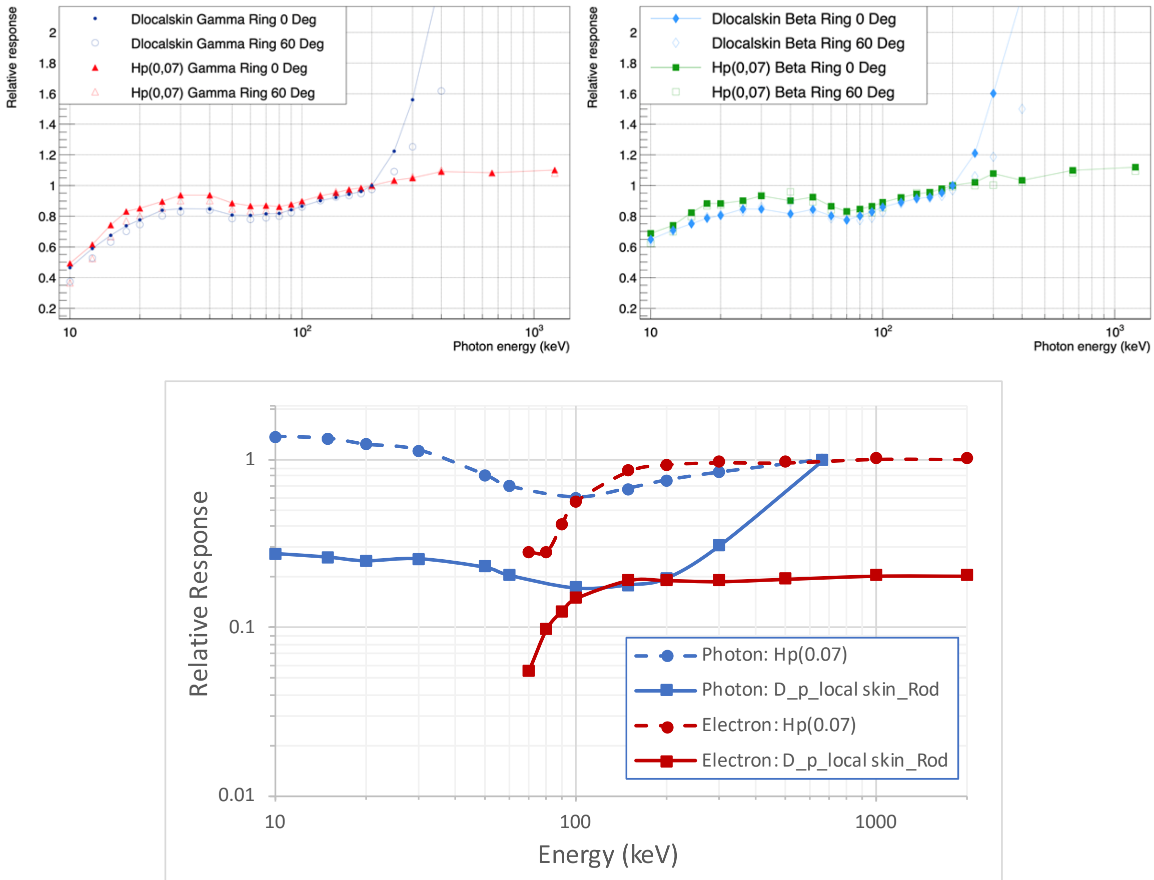

Figure 3.7 Effect of the new quantities on the response of extremity dosemeters. (Top) BeO ring design to (left) photons and (right) betas (Hoedlmoser *et al*, 2020); (Bottom) LiF:Mg,Cu,P finger-stall design.

Figure 3.7 shows that for these two approximately tissue-equivalent dosemeters, a photon energy dependence that was relatively flat in terms of $H_p(0.07)$ is worse in terms of $D_{p\ local\ skin}$ when the entire 10 keV – 1 MeV energy range is considered. In both cases the relative response would vary by a factor of ~5. Further, for the finger stall dosemeter especially, there is a significant divergence between the photon and beta $D_{p\ local\ skin}$ responses. Because extremity dosemeters are often designed to measure beta doses, they typically have thin filters; this limits the scope for redesign.

The features shown in the above figures are unlikely to be limited to BeO- or LiF-based passive detectors. Although data are not shown explicitly here, the responses of other common dosemeters, such as those based on the radio-photoluminescence (RPL) properties of silver-doped glasses, will also be affected. This impact may be particularly significant, considering that this material is less tissue-equivalent than, for example, lithium fluoride. These considerations are likely to rule out any future developments for single-element RPL glass dosemeters (e.g. for extremity dosimetry).

Note that the photon responses in the above discussion are based on the “full transport”, non-CPE conversion coefficients. The picture is different if the kerma approximation-based, CPE conversion coefficients are used instead. This is because, whilst low-energy photons are effectively in CPE anyhow in the skin, and hence it does not matter much whether CPE or full transport conversion coefficients are applied, the same is not true for the higher energy photon exposures used for the normalization. Thus, the choice of conversion coefficients employed for those makes a significant difference to the results. However, the Monte Carlo modelling that calculated the absorbed doses to the LiF or BeO during the dosemeter design process was performed assuming CPE at all energies, because that consistency is ultimately what would have to be employed during type-testing in a calibration laboratory. There is therefore a potential conflict of approaches, leading to a divergence that increases with energy if the non-CPE conversion coefficients are maintained. On the other hand, the severe photon energy dependence of response in figure 3.7 disappears if the CPE conversion coefficients are used instead throughout (see figure 3.20), as would the poor response to electrons also caused by the non-CPE-based N-300 or ^{137}Cs normalizations. This demonstrates the need to use the kerma-approximation, CPE, conversion coefficients for photon calibrations and type testing. For extremity dosemeters in particular, use of the full-transport, non-CPE, conversion coefficients would make it impossible to design a satisfactory extremity dosemeter.

3.3.1.2 Eye dosemeters

Figure 3.8 shows the effect of the new quantities on an eye dosemeter that uses BeO as an optically stimulated luminescence (OSL) sensitive element, for photon exposures; responses are normalized to the $D_{\mathrm{p\,lens}}$ or $H_{\mathrm{p}}(3)$ response (as appropriate) to the ISO Narrow Series N-150 X-ray field at 0° incidence. The implication is that the change to the quantities would leave the response largely unaffected above ~30 keV, but at lower energies the current small over-response of the dosemeter to $H_{\mathrm{p}}(3)$ would be exaggerated by the change in the quantities, resulting in a larger over-response to $D_{\mathrm{p\,lens}}$, albeit with the spread between 0° and 60° response somewhat mitigated.

Figure 3.8 also shows the effect of the new quantities on an eye dosemeter that uses LiF:Mg,Cu,P as a thermally stimulated luminescence (TLD) sensitive element, for monoenergetic photon and electron exposures; responses are normalized to the $D_{\mathrm{p\,lens}}$ or $H_{\mathrm{p}}(3)$ response (as appropriate) to the ^{137}Cs field at normal incidence. The implication is that the change to the quantities would leave the photon response largely unaffected above ~100 keV, but at lower energies the response would be increased: this would correct for the current under-response of the dosemeter at the lowest energy, but exaggerate the small over-response peaked at ~30 keV. For electrons, the shape of the response curve is relatively unaffected above ~2 MeV, though is lowered somewhat, which exaggerates the under-response exhibited for exposures at 60°. At lower energies, the angle dependence of the dosemeter becomes poor when responding in terms of the new dose quantity: the small under-response for exposures at 0°, 30° and 60° becomes a large over-response for exposures at 0° and 30°, but remains an under-response for exposures at 60°. This eye dosemeter incorporates a slab of 3mm tissue-equivalence that acts as a filter, which is unable to provide a dosimetric match for the curved profile of the realistic eye model used to derive $D_{\mathrm{p\,lens}}$.

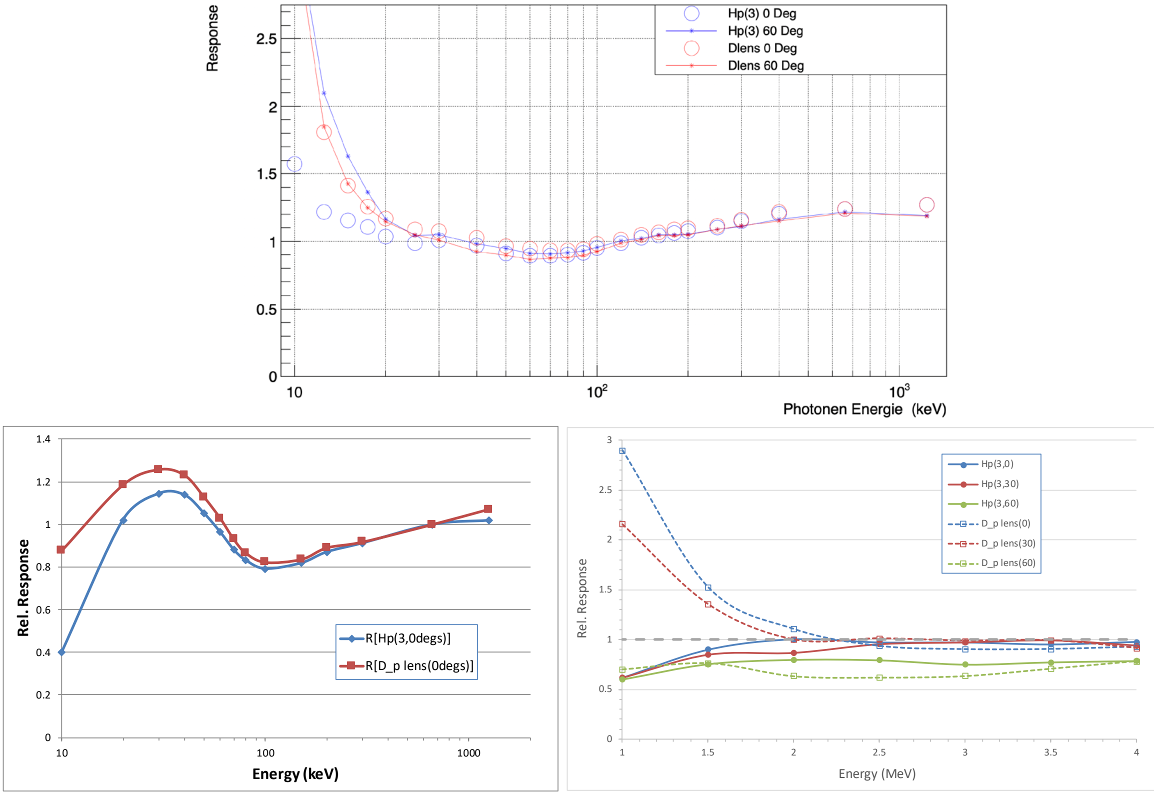

Figure 3.8 Effect of the new quantities on the responses of eye dosemeters. (Top) Photon response of a BeO design (Hoedlmoser *et al*, 2020). (Bottom left) Photon and (Bottom right) electron responses of a LiF:Mg,Cu,P design .

3.3.1.3 Whole-body dosemeters

Whole-body photon/electron dosemeters include:

- simple single-element dosemeters (often thermoluminescence (TL) type)
- two-element dosemeters (often either TLD or Optically-Stimulated Luminescence (OSL) type)
- multi-filter dosemeters, either with multiple elements or a single large-area element under several different filters (TLD, OSL or Radio-Photo-Luminescent (RPL) glass type; also direct ion storage (DIS) and electronic diode types)

Both the sensitive elements and the filters may be of:

- tissue-equivalent, or nearly tissue-equivalent, material, e.g. lithium fluoride, plastics.
- non-tissue equivalent material, e.g. phosphate glass, metals.

Figure 3.9 shows the effect of the new quantities on the 'skin' element of a whole-body dosemeter that uses BeO as an optically stimulated luminescence (OSL) sensitive element, for photon exposures; responses are normalized to the $D_{\mathrm{p\ local\ skin\ Slab}}$ or $H_{\mathrm{p}}(0.07)$ response (as appropriate) to the ISO Narrow Series N-300 X-ray field at 0° incidence multiplied by a calibration factor of 1.1×, which is the standard protocol for this dosemeter (Hoedlmoser *et al*, 2020). The implication is that the change to the quantities would leave the shape of the response relatively unchanged below ~200 keV, but the chosen normalization would lead to a consistent under-response in that range. A large over-response would be caused at higher energies, which compounds the effect. The divergence is probably caused by the assumption of kerma conditions for the $H_p(0.07)$ conversion coefficients but not for $D_{p\ \text{local skin Slab}}$, as discussed in Sections 3.3.1.1. and 3.4.

Figure 3.9 also shows the effect of the new quantities on the 'skin' element of a whole-body dosemeter that uses LiF:Mg,Cu,P as a thermally stimulated luminescence (TLD) sensitive element, for monoenergetic photon exposures at normal incidence; responses are normalized to the $D_{p\ \text{local skin Slab}}$ or $H_p(0.07)$ response (as appropriate) to the ^{137}Cs field. The implication is that the change to the quantities would leave the shape of the response relatively unchanged below ~200 keV, but the routine calibration to ^{137}Cs would lead to large under-responses at those energies and a severe energy-dependence overall.

Lastly, Figure 3.9 additionally shows the effect of the new quantities on the 'skin' element of three (labelled SC – 1, SC – 2 and SC – 3) types of whole-body active (electronic) personal dosemeter (APD), each of which uses a semi-conductor as its sensitive element (Ekendahl *et al*, 2020). The results correspond to exposures of the APDs to ISO Narrow-Series photon fields at normal incidence, and are plotted at the mean energies of those distributions. The data are normalized to the devices' respective $D_{p\ \text{local skin Slab}}$ or $H_p(0.07)$ responses to the ISO Narrow Series N-150 X-ray field so that comparisons may be made, but it is noted that this source may not necessarily be the optimum calibration recommended by a given manufacturer. It is clear that the change to the quantities would have little impact to the responses of the APDs below ~165 keV, but would increase the responses at higher energies. For two of the APDs, this increase would transform small under-responses into small over-responses, which would be considered acceptable; for the third APD, however, the current small over-response would become larger.

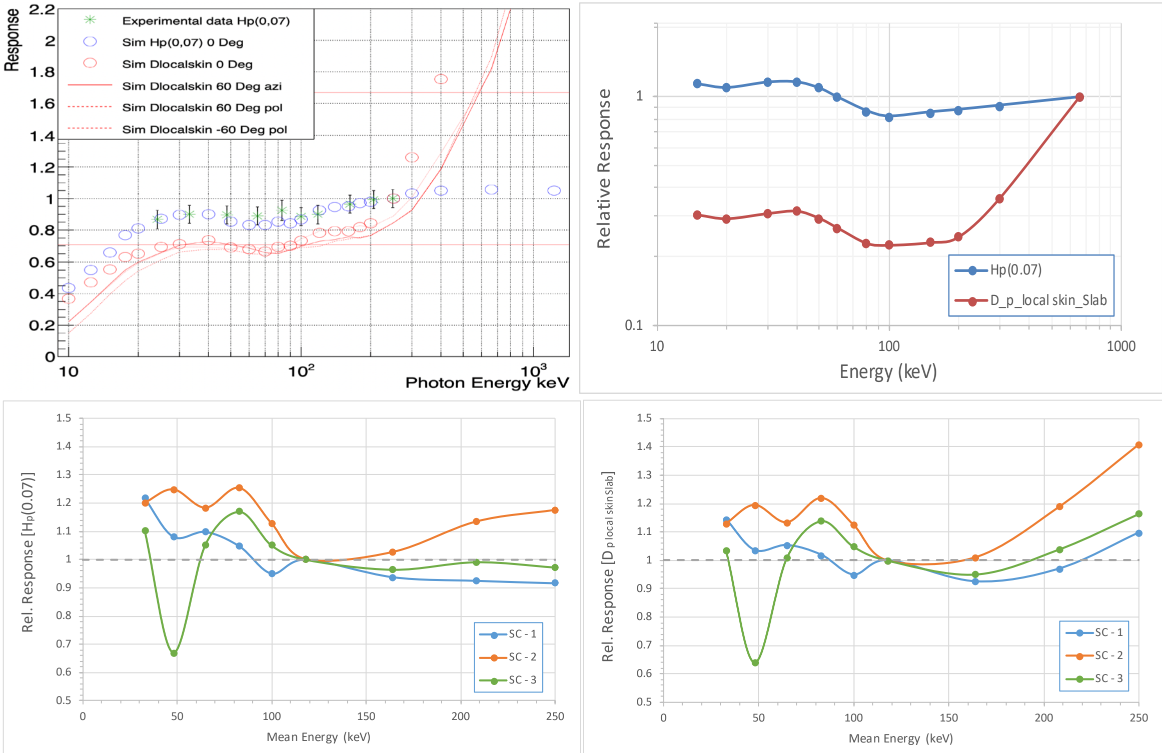

Figure 3.9 Effect of the new quantities on the skin element of whole body dosemeters. (Top left) Photon response of a BeO dosemeter [Hoedlmoser *et al*, 2020]. (Top right) Photon response of a LiF:Mg,Cu,P dosemeter at normal incidence. (Bottom left) Photon $H_p(0.07)$ and (Bottom right) $D_{p\text{ local skin Slab}}$ responses of 3 APDs at normal incidence, data replotted from [Ekendahl *et al*, 2020].

Figure 3.10 shows the effect of the new quantities on the 'body' element of a whole-body thermoluminescence dosemeter (TLD) that uses LiF:Mg,Cu,P as its sensitive material, for monoenergetic photon exposures; responses are normalized to the $H_p(0°)$ or $H_p(10,0°)$ response (as appropriate) to a ^{137}Cs gamma field (Eakins *et al*, 2019). The dashed lines on the figures denote the limits currently recommended by the International Electrotechnical Commission (IEC) (IEC, 2012) for photon personal dose equivalent. Data at a range of angles, and for both rotationally and spherically isotropic exposures, are shown. It is clear that the change to the dose quantity 'over-corrects' the $H_p(10)$ under-response at the lowest energies and amplifies the over-response in the ~20-50 keV range, with a large H_p instead exhibited. Above ~100 keV, however, the performance of the TLD is relatively unaffected.

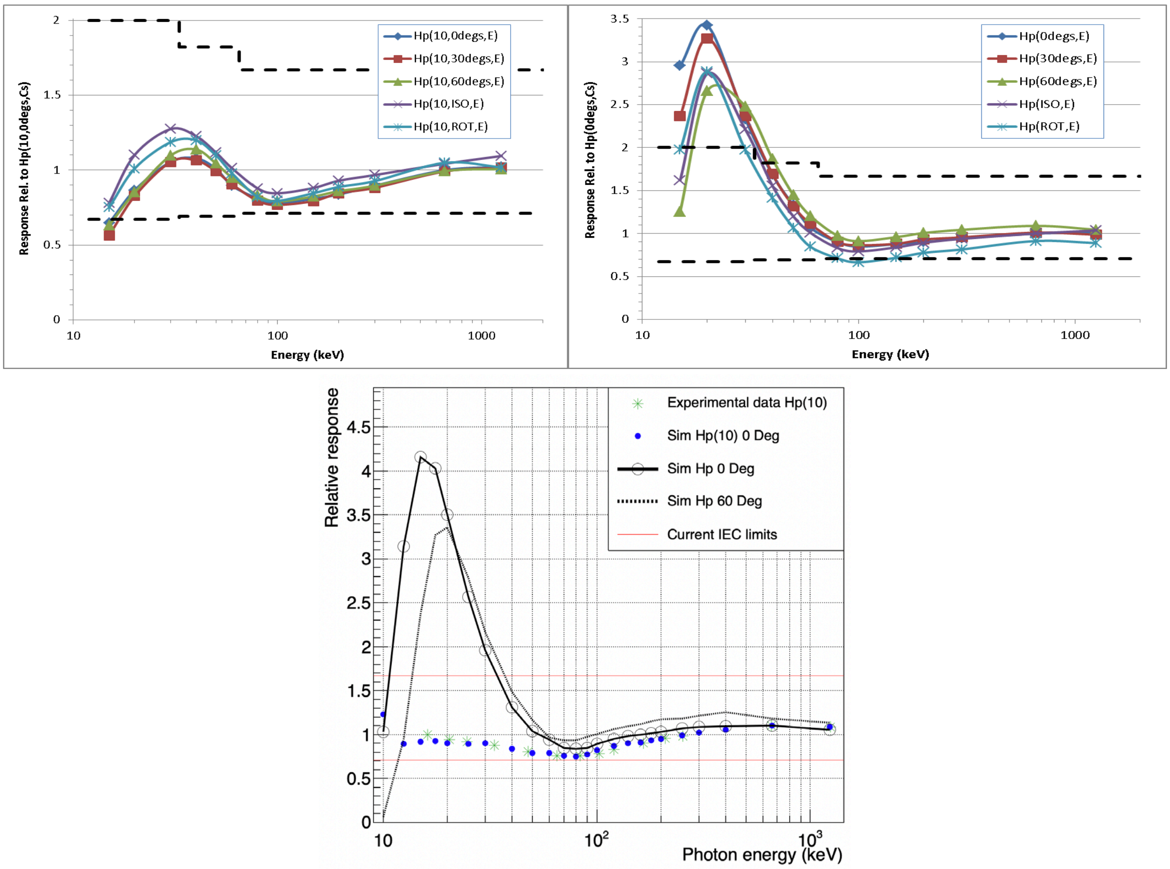

Figure 3.10 Effect of the new quantities on the body element of whole body dosemeters. (Top left) Photon relative $H_p(10)$ response of a LiF:Mg,Cu,P dosemeter; (Top right) Photon relative H_p response of a LiF:Mg,Cu,P dosemeter (Eakins *et al*, 2019); (Bottom) $H_p(10)$ and H_p responses of a BeO dosemeter (Hoedlmoser *et al*, 2020). The dashed lines show the current IEC limits.

The data in Figure 3.10 relate to a TLD that uses LiF:Mg,Cu,P as its sensitive element, which has good tissue equivalence. Different response characteristics are anticipated for TLDs that use alternative materials. For those that employ LiF:Mg,Ti, which is less tissue-equivalent and typically over-responds more at energies <~100 keV (Cardoso and Lacerda, 2021; Luo, L, personal communication, June 2021), the change in the dose quantity from $H_p(10)$ to H_p will exacerbate that over-estimate. This will make redesign of all such dosemeters necessary in order to regain satisfactorily flat response characteristics across the required energy and angle ranges. Such a process is likely to be costly, and difficult to achieve; in some cases the challenges may even prove insurmountable, with the requirement to respond in terms of the new quantities precluding the use of some sensitive materials.

Figure 3.10 also shows the effect of the new quantities on the 'body' element of a whole-body OSL dosemeter that uses BeO as its sensitive materials, for photon exposures; responses are normalized to the $H_p(0°)$ or $H_p(10,0°)$ response (as appropriate) to a ^{137}Cs source at 0° incidence multiplied by a calibration factor of 1.1×, which is the standard protocol for this dosemeter (Hoedlmoser *et al*, 2020). The implication is that the change to the quantities would leave the response largely unaffected above ~100 keV, and between ~50-100 keV would mitigate against the current small under-response to $H_p(10,0°)$, but at lower energies the current flat-response would become a large over-response to H_p.

Figure 3.11 shows the effect of the new quantities on the 'body' element of a number of different whole-body electronic personal dosemeters (APD) (Ekendahl *et al*, 2020). Ten of these (labelled SC- 1 to SC – 10) use semi-conductors as their sensitive elements, whilst two (labelled GM- 1 and GM – 2) use a Geiger-Müller tube; for comparison, data are also shown for a four-element passive TLD using Harshaw-700H LiF:Mg,Cu,P as its sensitive material. The results correspond to exposures of the APDs to the ISO Narrow-Series fields at normal incidence, and are plotted in Figure 3.11 at the mean energies of those distributions; data have been normalized to the APDs' respective responses to ^{137}Cs so that comparisons may be made, but it is noted that this source may not necessarily be the optimum calibration recommended by a given manufacturer. It is clear that the change to the quantities would have little impact to the responses of the APDs above ~100 keV, but would generally increase their responses at lower energies. For some of the APDs this increase would mitigate against a large under-response, whilst for others (and the TLD) it could lead to significant over- responses; the effects would be greatest at the lowest energy of interest.

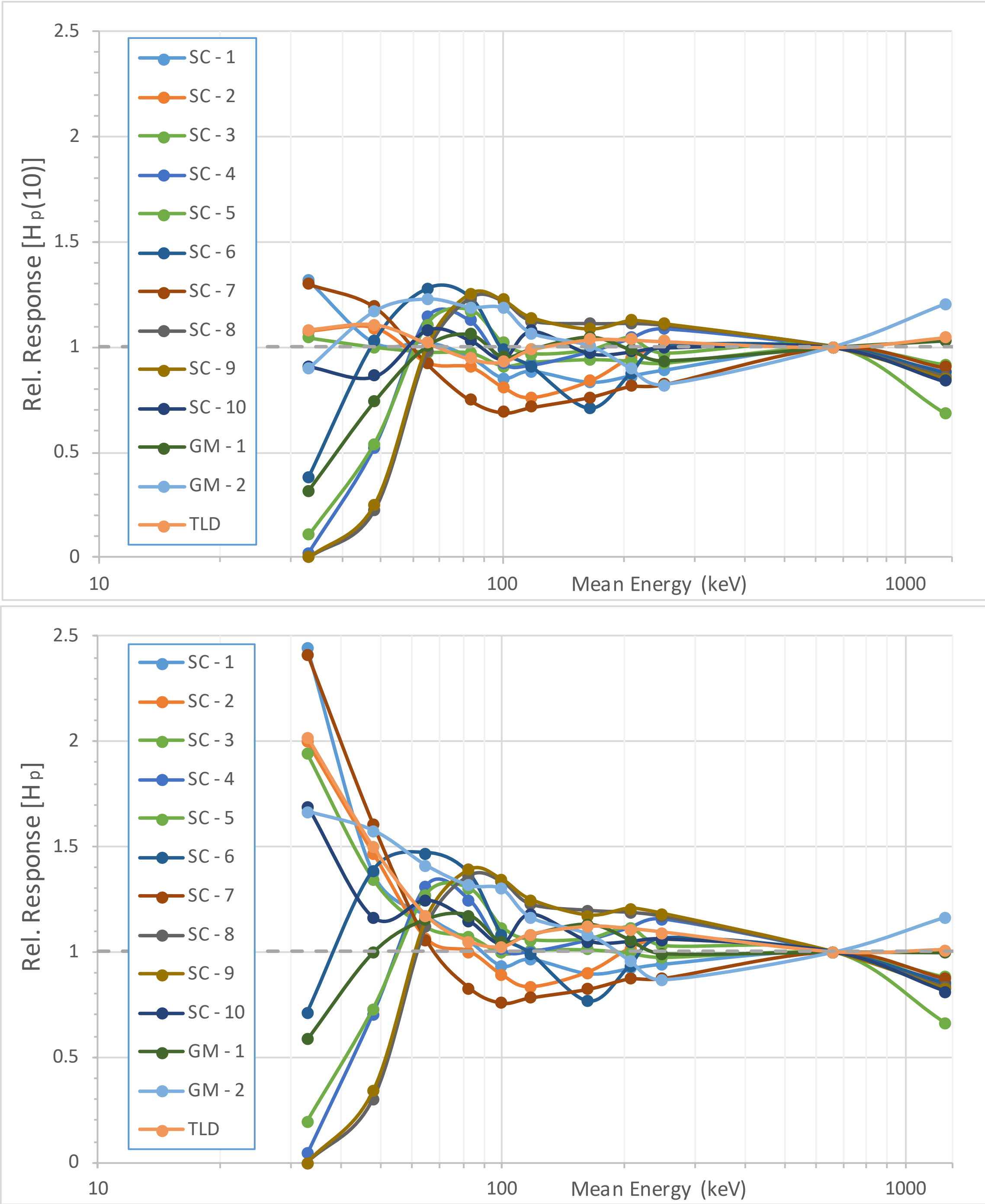

Figure 3.11 Effect of the new quantities on a range of APDs. (Top) $H_p(10,0°)$ photon response. (Bottom) $H_p(0°)$ photon response. Data replotted from (Ekendahl *et al*, 2020).

The features shown in the above figures are unlikely to be limited to APD active dosemeters or BeO- or LiF-based passive detectors. Although data are not shown explicitly here, the responses of other common dosemeters, such as those based on the optically stimulated luminescence (OSL) of doped aluminium oxide (Al_2O_3:C) or the radio-photoluminescence (RPL) properties of silver-doped glasses, will also be affected. These are typically multi-filter types, with dose determination made by a sophisticated algorithm. The impact may be particularly significant, considering that these materials are less tissue-equivalent than, for example, lithium fluoride.

Multi-filter dosemeters (RPL, OSL, TLD, film badge) typically depend on algorithms to measure the operational quantities. Widely-used types include an OSL dosemeter that uses multiple Al_2O_3:C elements, a whole-body RPL glass dosemeter that has five energy compensation filters for assessing photon and beta exposures, and four-element TLDs using LiF. Some manufacturers have reported that detailed work has yet to be carried out, but are confident that algorithms could successfully be adjusted to provide a reasonable estimate of H_p (Million M, personal communication June 2021; Koguchi Y, personal communication June 2021; Luo L, personal communication June 2021). Such adjustment will have associated costs, and type-testing based on the new algorithms will be necessary. They report that the effect on measurement uncertainties is, likewise, not yet established.

The performance of a three-element whole-body TLD in terms of personal dose has recently been explored [Polo *et al*, 2021], featuring $CaSO_4$:Dy plus polytetrafluoroethylene (PTFE) detectors sandwiched between different filters inside an acrylic badge. In that work, the anticipated H_p response of the dosemeter was compared against the current $H_p(10)$ response for 0°, 45° and 60° exposures to a range of ISO Narrow Series fields (N-30, N-40, N-60, N-80, N-100, N-120) and ^{137}Cs, with that latter used for the calibration. The authors showed that the change in the dose quantity would lead to poorer performances, especially at lower energies and higher angles of incidence, and concluded that a redesign of the filter set and an upgrade of the calculation algorithm would be needed to better comply with the requirements of the new quantity. The adoption of a sensitive material other than $CaSO_4$:Dy may also be considered preferable due to its energy dependence, which the authors comment would need to be imported and would be associated with cost implications.

Multi-filter dosemeters that use newer materials, for example high Z_{eff} OSL materials such as $YAlO_3$:Mn^{2+} or Lu_2O^{3-} that have high sensitivity and pronounced energy response dependence (Zhydachevskii *et al*, 2016, Chumak *et al*, 2017), will need to be designed with the new quantities in mind. Likewise, it may be possible to optimise the angular dependence of response (Chumak *et al*, 2011).

Figure 3.12 shows the effect of the change from $H_p(10)$ to H_p for a hybrid dosemeter that uses direct ion storage (DIS) technology, for exposures to the ISO Narrow-series; the datapoints are plotted at the mean energies of those X-ray fields. In both cases, normalization to S-Cs has been chosen, with a scaling factor of 1.2 applied to allow a direct comparison, and responses for both 0° and 60° exposures are included. The air kerma to H_p conversion coefficients that were applied were derived using data published recently for these fields (Otto, 2019b). The implication from Figure 3.12 is that the change in the dose quantities would lead to large over-responses at low photon energies, improve the small under-response currently seen for the fields with mean energies between ~40 and ~80 keV, but there is no significant effect to the response at higher energies. The current acceptance limits recommended by IEC are also superimposed on Figure 3.12. Whilst it must be reiterated that these are defined in terms of $H_p(10)$, and so cannot therefore necessarily be deemed appropriate to assess H_p performances, it is remarked that the over- and under-responses of the current dosemeter in terms of $H_p(10)$ always meet these criteria, but the large over-response for H_p at low energies would greatly exceed the permitted maximum limit.

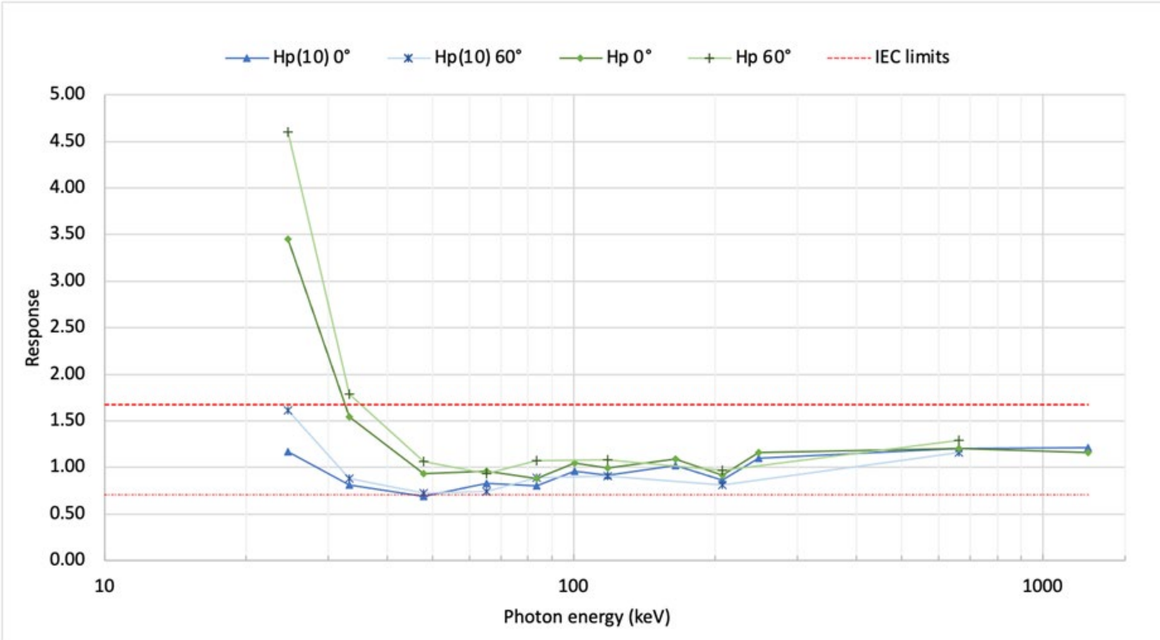

Figure 3.12 Effect of the new quantities for photons on a whole-body hybrid dosemeter that uses DIS technology.

The range of a 2 MeV electron in tissue is approximately 10 mm (ICRU, 1984); no electron or beta source with an energy below 2 MeV will therefore contribute to $H_p(10)$ directly, However, electrons of all energies will deposit dose within the voxel elements representing the skin, so will contribute to effective dose, and hence H_p; the implication, therefore, is that in electron or electron-photon mixed fields, a good dosemeter ought to be able to respond down to arbitrarily low energies. Figure 3.13 shows the electron responses of the covered and uncovered elements of a thermoluminescence dosemeter (TLD) that uses LiF:Mg,Cu,P as its sensitive material; the uncovered element is currently intended to assess $H_p(0.07)$, whilst the covered element uses 10 mm of tissue-equivalent filtration to assess $H_p(10)$. It is clear that neither element is able to make reliable estimates of H_p for electrons with energies below ~15 MeV. Although it may be commented that whole-body beta exposures in the workplace are perhaps unlikely to be a very large component of an individual's overall dose, intermediate-energy electrons may be more prevalent in the vicinity of accelerators, and moreover it is perhaps reasonable to suggest that if H_p is defined and conversion coefficients exist for a given particle at a given energy, the quantity ought to be measurable.

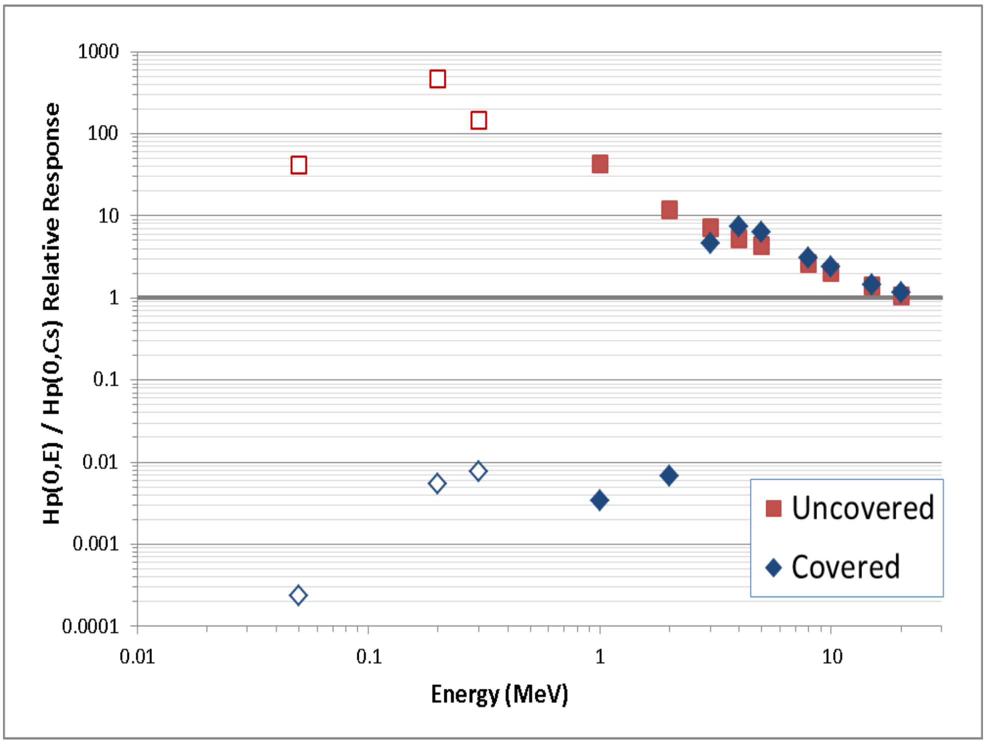

Figure 3.13 Electron $H_p(0°)$ relative responses of both the covered and uncovered elements of LiF:Mg,Cu,P TLD relative to their respective $H_p(0°,Cs)$ calibration responses. Filled symbols denote monoenergetic exposures, whilst empty symbols denote beta exposures plotted at their mean energies: ~0.05 MeV for ^{147}Pm, ~0.2 MeV for ^{85}Kr and ~0.3 MeV for ^{90}Sr/^{90}Y (Eakins *et al*, 2019).

Lastly, figure 3.14 shows a comparison of relative responses, *R*, following a proficiency test performed in terms of both $H_p(10)$ and H_p (Caresana *et al*, 2021), using S-Cs and wide spectrum radiation qualities (ISO4031 W-series: W-60, W-80, W-110 (0° and 45°) and W-300), i.e. different from calibration radiation qualities (typically N-series), for three photon dosimetry systems (labelled S1, S2 and S2) exposed to a range of doses (0.1 - 100 mSv); the applied doses on the abscissae are given in terms of $H_p(10)$ (left plot) and H_p (right plot), and the results are normalized to the reference irradiation dose. The conversion coefficients for H_p were calculated from the kerma-approximation (CPE) values as suggested for calibration and type testing. The dosimetry systems used multi-filter badges. Two of them (S1 and S2) employ two TLD-100 elements, one shielded with 1.5 mm Al and one unshielded. S3 used four elements (two $Li_2B_4O_7$:Cu and two $CaSO_4$:Tm). In each case, the participants modified their respective dosemeter response functions by applying the new conversion coefficient and tuning the dose calculation algorithm to optimize it in terms of H_p. The dosemeter badges were not modified, however.

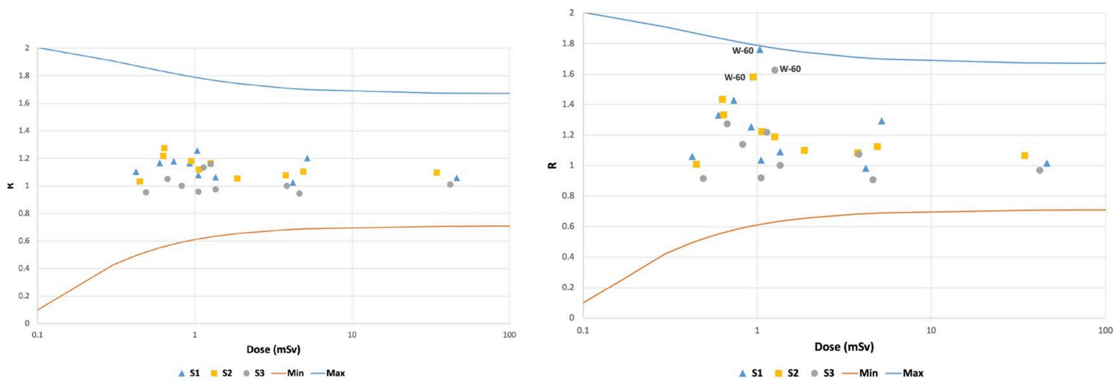

Figure 3.14 Results from an intercomparison exercise, showing relative $H_p(10)$ response (left) and relative H_p response (right), for three different dosimetric systems exposed to S-Cs and W-series fields (Caresana *et al*, 2021). The conversion coefficients for H_p were calculated from the kerma-approximation (CPE) values as suggested for calibration and type testing.

The three systems performed well in terms of $H_p(10)$, as expected, while the performance in terms of H_p appears worse. Also as expected, an energy dependence of response was demonstrated (Caresana *et al*, 2021), with the worst result found for the W-60 field (as highlighted in Figure 3.14 (right)), although all datapoints – based on the use of the kerma-approximation conversion coefficients – are still within the trumpet curve limits recommended by the standard (ISO 14146, 2018). This study covers a limited number of irradiations and a limited number of dosimetric systems, however it gives some indication about the complication of moving to the new dosimetric quantities without changing the badge design.

3.3.1.4 Neutron Personal Dosemeters – Track Etch

Figure 3.15 shows the effect of the new quantities on a track-etch detector that uses electrochemically etched poly-allyl diglycol carbonate (PADC) encased in nylon to estimate whole body doses for neutrons; responses are normalized to the $H_p(0°)$ or $H_p(10,0°)$ response (as appropriate) to an ^{241}Am-Be source, with data provided for both AP (0°) and rotationally isotropic (ROT) monoenergetic fields. It is clear that the impact from changing the dose quantity is more extreme for frontal fields (AP) than rotational fields, indicating that the ICRU proposal will introduce a greater angle-dependency to the dosemeter response. The change from $H_p(10)$ to H_p is also seen to lessen the under-response at intermediate energies, but increase the over-response at thermal energies and the peak around 1 MeV; although the former of these represents an improvement, it is noted that the latter are more important in terms of radiological risk and are relevant to workplace field exposures.

Also compared in Figure 3.15 are the performances of the PADC dosemeter in the 19 workplace neutron fluence-energy distributions that were determined during the EVIDOS project (Schuhmacher *et al*, 2006); data are plotted at the mean conversion coefficient for each field, and re-scaled to the respective optimum calibration response for the dosemeter. In both cases, a wide range of results is observed, though the standard deviation for $H_p(10)$ is a little smaller than for H_p. Moreover, it is clear that the $H_p(0°)$ responses are considerably and consistently higher than the H_p(ROT), whilst this trend appears less defined for $H_p(10)$. As before, the observation is that the PADC dosemeter will find it hard to assess doses accurately in neutron fields with strong directional dependence.

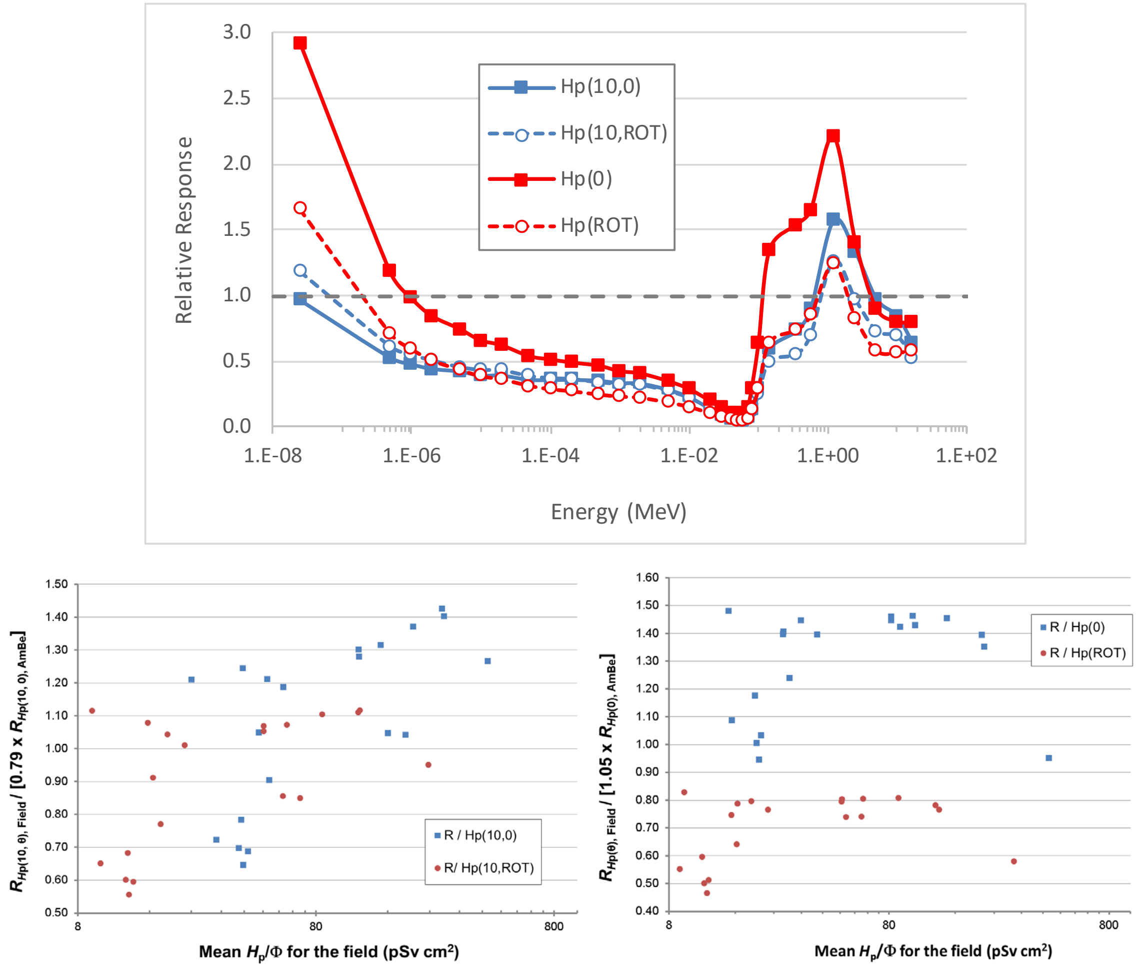

Figure 3.15 Effect of the new quantities on a track-etch whole body neutron dosemeter. (top) Relative responses in idealized monoenergetic fields. (bottom) Responses in workplace fields [Tanner *et al*, 2019].

The neutron dosemeter corresponding to the above figures is a single PADC element design, encased in a nylon holder. Although data are not shown here for alternative designs, for one that consists of a CR-39 element with two converters / radiators, one being high-density polyethylene (HDPE) for fast neutrons and the other boron nitride (BN) for thermal neutrons, it is estimated that the changes to the dose quantities may be partially mitigated by changing the etching conditions (e.g. temperature, etching time), the microscopy conditions, and/or the dose calculation algorithm used to reconstruct the doses (Koguchi Y, personal communication June 2021). Similarly, algorithms based on the etched track morphology may be able to be adjusted to assess H_p (Million M, personal communication June 2021), although it is not yet known how effective this could be.

3.3.1.5 Neutron Personal Dosemeters – Albedo

Albedo dosemeters are typically multi-filter TLDs that include detectors which are sensitive to thermal neutrons alongside detectors which are not. Agreed correction factors, particular to specified workplace field categories, are used to derive the fast neutron component. The dosemeters also measure photon dose.

As regards the new operational quantities, the situation for albedo dosemeters is similar to that for multi-filter photon dosemeters (Haninger T, 2021). Work has yet to be done to evaluate the impact. No significant design changes are anticipated, but a thorough review and update of the correction factors will be needed. This will need to consider the neutron energy spectra and their angular distributions in the various classes of workplace field. For this, the availability of a full range of conversion coefficients will be crucial. Again, it is not possible at this stage to conclude what the effects on measurement uncertainty will be.

The situation for albedo neutron dosemeters will be complicated by any changes to the intrinsic photon response of the TLD material used, for example LiF:Mg,Ti (see 3.3.1.3 above).

3.3.2 Survey instruments

3.3.2.1 Directional monitoring

Figure 3.16 shows the effect of the change to the quantities on alternative designs of photon / beta directional survey instrument that are intended to respond in terms of $H'(0.07)$. One of the instruments is an ion chamber (IC) design, the other is a thin end-window pancake Geiger-Müller (GM) tube with a compensation (filter) cap. Response data are provided for ^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y beta spectra for both instruments, and also to the N20 and N40 low-energy Narrow Series X-ray fields for the IC design; only data at normal incidence were available, however. The results are plotted at the approximate mean energies of the fields, and are normalized to the devices' respective responses to ^{137}Cs, assuming sufficient build-up during calibration, though it is noted that this may not necessarily be the optimum approach recommended by a given manufacturer. The conversion coefficients relating to the slab phantom have been assumed for $d'_{\text{local skin}}$.

It is seen that the relative responses to $D'_{\text{local skin Slab}}$ will generally be a little lower than those for $H'(0.07)$, especially for the low-energy electrons from the ^{147}Pm source. Overall, however, the impact is not large, noting that the shifts of up to ~20 % caused by the change in the dose quantity are considerably less than the variations in response across the energy range for a given quantity.

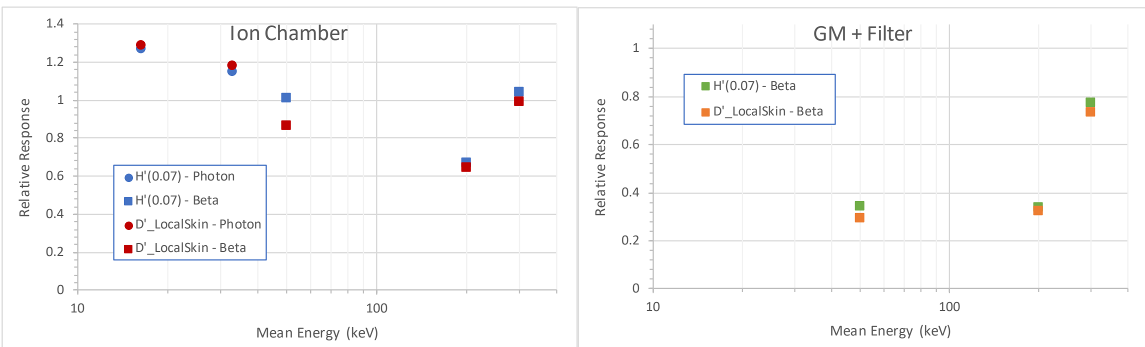

Figure 3.16 Effect of the new quantities on 2 different photon / electron directional survey instruments for monitoring $H'(0.07)$. Only data at normal incidence were available. (left) Ion chamber design; (right) Compensated GM tube.

3.3.2.2 Area monitoring

Figure 3.17 shows the effect of the change to the quantities on four alternative designs of neutron survey instrument, labelled NSI - 1 to NSI – 4, to monoenergetic isotropic neutron exposures. The data are normalized to the devices' respective responses to ^{241}Am-Be, so that comparisons may be made, but it is noted that this source may not necessarily be the optimum calibration recommended by a given manufacturer. The black lines in Figure 3.17 indicate the *H**(10) performance criteria currently recommended by the standard (IEC, 2014); these are included for general guidance, though would presumably also be revised and updated by IEC once *H** had replaced *H**(10). It is clear that the impact of the change will be both energy- and design-specific. For example, the responses of all instruments at the lowest energies will be increased: this will be advantageous to NSI – 1, NSI – 3 and NSI - 4, which currently under-respond, but detrimental to NSI - 2, which currently performs well. Similarly, the under-responses of the NSI – 2, NSI – 3 and NSI - 4 in the 0.1 – 3 MeV range, which is of particular importance to neutron workplace fields, will be largely removed by the change, whilst the NSI - 1, which currently performs well, will over-respond significantly, At the highest energies, for which only the NSI – 2 is appropriate, the under-response will be increased significantly.

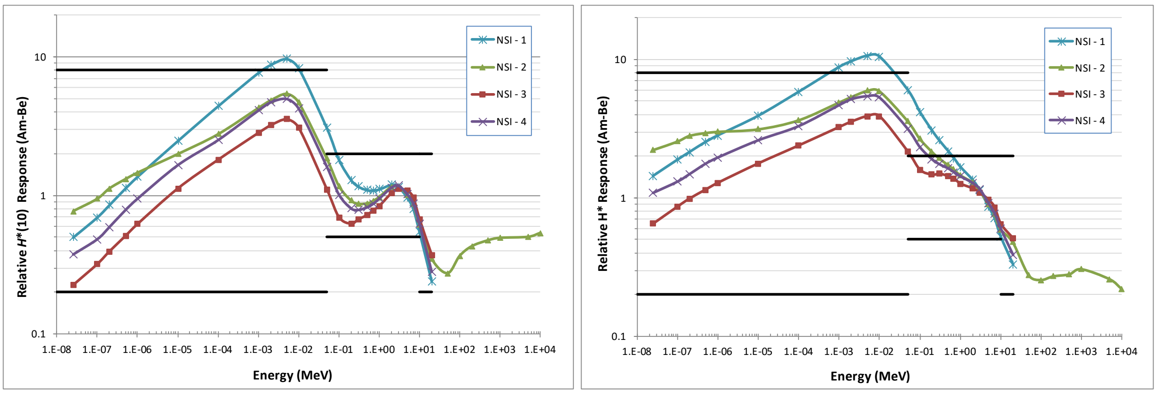

Figure 3.17 Effect of the new quantities on 4 different neutron survey instruments. (left) *H**(10) responses; (right) *H** responses.

Figure 3.18 shows the effect of the change to the quantities on different designs of photon survey instrument. The top left and right plots provide data for four alternative instruments (labelled *A*, *B*, *C* and *D*) that use Geiger-Müller tubes as their active components, but are constructed differently from different materials and with differing compensating filters to give differing energy responses; data are normalized to the devices' respective responses to ^{137}Cs. It is clear that the impact of the change will be relatively low, apart from at the lowest energies, where all of the instrument responses will be increased. However, whether this increase is advantageous or disadvantageous is instrument-specific. For instrument *C*, for example, which has a metal-walled design, the current severe under-response to *H**(10) is largely 'corrected' in its *H** response; conversely, for instrument *B*, which has an end-window design, the current good *H**(10) response at low energies becomes a large over-response to *H**.

Figure 3.18 also shows the *H**(10) and *H** responses of a passive area device that was designed by modifying a personal dosemeter badge featuring BeO detector elements (Hoedlmoser *et al*, 2020). The device has a lead and tin filter combination on one element and a plastic scattering body surrounding the second detector; a nonlinear algorithm is then used to reconstruct the dose quantity from the measured readings, with calibration based on the elements' combined response to an N-300 exposure at 0° incidence. It is clear that the area dosemeter will over-respond to *H** at all energies, but this becomes particularly severe at energies below ~50 keV.

A 2 MeV electron travels about 10 mm in tissue (ICRU, 1984), so most beta radiation sources should not contribute directly to *H**(10). Photon ambient dose equivalent instruments are therefore designed to have effectively zero response for common reference beta sources. However, electrons of all energies will contribute directly to *H**, so use of a photon ambient dose instrument in mixed photon/electron fields ought to be able to respond to its electron component down to arbitrarily low energies. Clearly, this will be difficult to achieve for all current designs of instrument, with maximal under-responses anticipated.

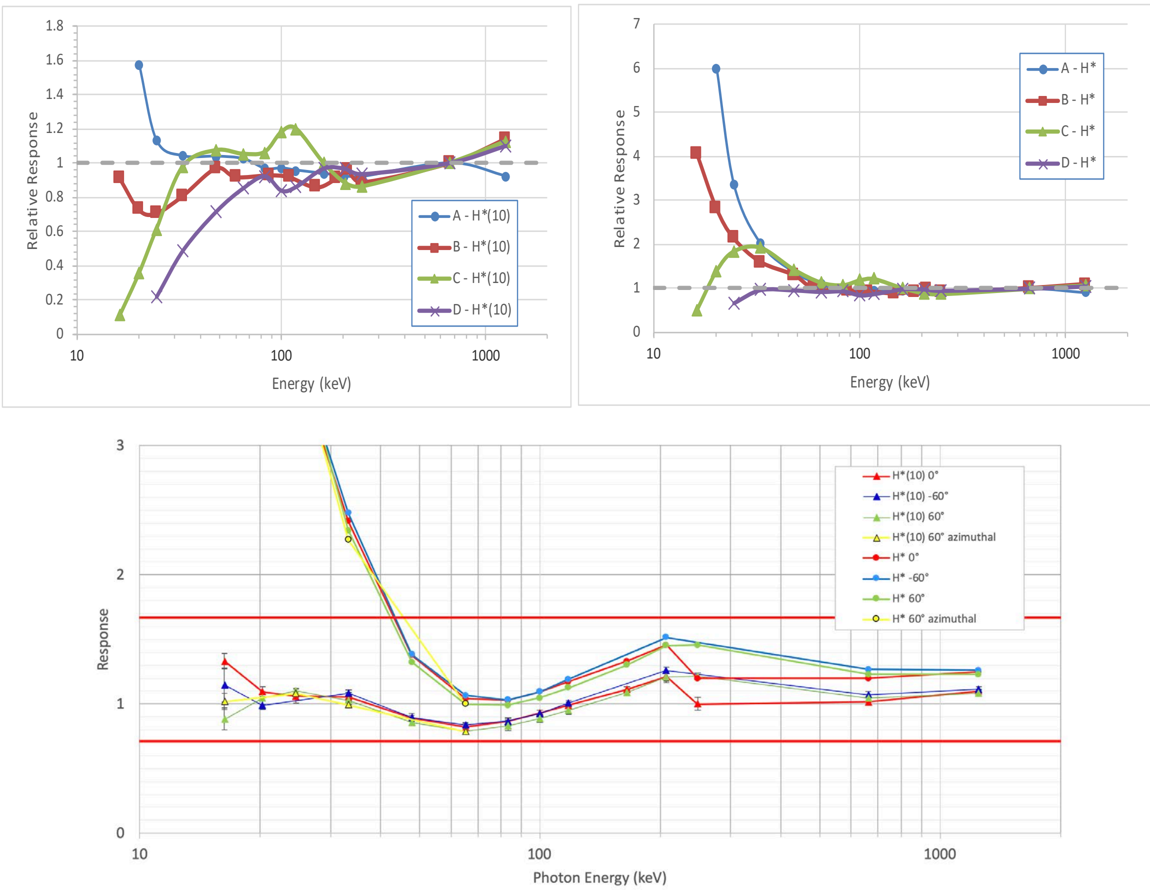

Figure 3.18 Effect of the new quantities on photon survey instruments. (Top left) *H**(10) responses and (Top right) *H** responses of active GM-tube based designs. (Bottom) *H**(10) and *H** responses of a passive BeO design.

3.4 Space and Airflight

3.4.1 Radiation fields in Space

For the assessment of radiation exposure of astronauts in space, ICRP 123 considers that the application of radiation weighting factors and, as a consequence, derived quantities such as the effective dose, are not appropriate (ICRP, 2013). Rather, ICRP123 recommends the application of quantities derived from the linear energy transfer (LET) distributions, for instance organ dose equivalents or the whole-body effective dose equivalent. Thus, the new operational quantities defined by ICRU, which are based on radiation weighting factors, are not relevant for the assessment of radiation exposure of astronauts in space. In fact, these quantities have to be considered specifically inapplicable, due to the overestimation of the effective dose using the radiation weighting factor instead of the quality factor for high energy heavy ions, which are encountered in exposure situations in space.

The measurements done so far in spacecraft are mainly for the control of the environment, and aim to give a rough estimate of the exposure rather than to be used in calculating risks. To collect the most complete information, a variety of instruments is used. Examples include: integrating dosemeters, such as various types of thermoluminescence dosemeters (TLDs) and nuclear track particle detectors (NTPD); Direct Ion Storage (DIS) detectors; a variety of silicon particle spectrometers; different types of scintillators; and tissue-equivalent proportional counters, TEPC[3]. The TEPC was for a long time considered as a reference instrument for space experiments, but it no longer has this status. The most modern detector is the Timepix detector, a hybrid pixel detector developed by CERN, which is part of the Hybrid Electronic Radiation Assessor (HERA) detection system on the ORION spacecraft. This detector will be used in the future by NASA in the Artemis programme, and certainly used in Lunar Orbital Platform-Gateway (a planned small space station in lunar orbit). All detectors used in space undergo a very intensive calibration program, using reference fields for photons and neutrons, and proton and heavy ion accelerators.

Following ICRP 123, the determination of the effective dose equivalent, which is chosen as the best measure of detriment for space radiation fields, should be carried out using the following approaches:

- Assessment of the radiation field parameters at the location of the astronaut (measurement of particle type, and energy and direction distributions of fluence), and the application of appropriate fluence to dose conversion factors for each particle type.
- Calculations of organ absorbed doses, using: as input, particle and energy spectra, and direction distributions of fluence from outside the spacecraft obtained from benchmarked radiation models; and a code that can perform radiation transport into the spacecraft into the human body.

3.4.2 Radiation fields at aviation altitudes

The assessment of doses to aircrew is routinely performed using numerical models. These model calculations are typically validated with in-flight measurements using tissue-equivalent proportional counters, which are calibrated to ambient dose equivalent $H^*(10)$ by the use of reference fields. However, other measurement set-ups have also been used – a good compilation is provided elsewhere (Lindborg *et al*, 2004). It has been shown in several campaigns that the $H^*(10)$ measurements of the TEPC provide the best estimates of effective dose in that environment (e.g. Kyllönen *et al*, 2001; Latocha *et al*, 2006; Lindborg *et al*, 2007).

Since the new ICRU report states that the ICRU sphere bears no resemblance to the human body, in which the protection quantity effective dose is defined, the most important change may result from the fact that although the TEPC provides a good approximation of $H^*(10)$, it is not able to directly measure the required new quantity, which is based on fluence and energy spectra data. First model estimates of the new quantity H^* indicate that it overestimates $H^*(10)$ under conditions prevailing

[3] A very good source of information is the webpage (www.wrmiss.org) of the annual workshop on radiation monitoring on the ISS (WRMISS).

in aviation by about 10% and *E* by about 30% (Matthiä *et al*, 2022). Measurements performed with a TEPC calibrated to *H*(10)* may then be converted to *H** by applying a correction factor of 1.1.

Besides numerous calibrations in reference fields resembling radiation conditions in atmosphere (like CERN-CERF), including also Bonner spheres, very good agreement has been demonstrated between the ambient dose equivalent measurements with the TEPC and Monte Carlo calculations (e.g. Rollet *et. al*, 2007). The galactic cosmic ray (GCR) model that was used was benchmarked with satellite and balloon (ACE/CHRIS and BESS) data. The coupling of *E* and *H**(10) in terms of their respective dependencies on altitude, cut-off rigidity (R_c, related to magnetic latitude) and solar cycle has also been shown (Matthiä *et al*, 2014). The results demonstrate that even in the case that knowledge of the characteristic dependencies of the radiation field at travel altitudes is unknown, the coupling varies in the range of 6%. Under the assumption of a coupling factor of 0.835, this leads to a deviation of about 3%. As TEPC measurements are mostly used for quality assurance within the frame of dose assessment with model-calculated effective dose, an adaptation of the old operational quantity to the new operational quantity is not necessary. So, there is no reason why the TEPC needs to be replaced for estimating of the effective dose, especially if there are no suitable alternatives. Further, determination of *H** requires spectral measurements, in aircraft fields, which are not yet available.

3.5 Potential improvements and solutions for dosimetry

The previous sections discussed the potential positive and negative impacts of the new operational dose quantities on the response characteristics of existing designs of dosemeter and instrument. It is natural next to consider what steps might need to be taken in order to mitigate or avoid the negative impacts, whilst keeping the positive. Such steps might logically fall into three categories, discussed below:

- recalibrations of the dosemeters and instruments;
- redesigns of the dosemeters and instruments; and
- revision of the ways in which of the dosemeters and instruments are employed.

For completeness, the impacts of the proposals are also discussed briefly here for online dosimetry, which is a recent proposal intended to remove the need for personal dosemeters, using modelling to determine doses directly to individuals in real-time.

3.5.1 Recalibrations of the dosemeters and instruments

3.5.1.1 Using a Different Calibration or Normalisation

In situations for which a fairly flat H_p(d), *H*(d) or *H**(10) response has been raised or lowered to become a fairly flat over- or under-response to H_p, D_p, *D′* or *H**, it might be possible to mitigate the impact by recalibrating the dosemeter or instrument using an alternative radiation source, or by applying an appropriate calibration factor, to globally shift the response downwards or upwards.

For example, consider an instrument that is normally calibrated to ^{137}Cs and that, under the new operational quantities, shows an unacceptably large under-response at low energies but only a small over-response at higher energies. Either by changing the radiation quality used for calibration, in this case to a source lower in energy than ^{137}Cs, or by applying a scaling factor to the ^{137}Cs calibration, it is possible to make those over-and under- responses more equal, and the overall instrument response may therefore become acceptable.

It may also be possible to simply adjust the intrinsic calibration of an instrument. However, this is not possible for some instruments: even with a new calibration factor, the indication of the monitor will still give the same value, and recalculation of the doses is needed after the measurements.

This suggestion is illustrated for a neutron survey instrument in Figure 3.19 (Eakins *et al*, 2018), where the effects are shown of recalibrating the NSI-2 from its current ^{241}Am-Be calibration response to its responses at either 144 or 565 keV; the NSI-2 instrument was chosen somewhat arbitrarily for illustration, and because its responses are close to the mean responses at those intermediate energies of the four neutron survey instruments shown previously in Figure 3.17. It is clear that recalibration to either of these energies reduces the over-response to H^* that is exhibited across most of the instrument's intended energy range when calibrated using ^{241}Am-Be, albeit at the expense of the response at the highest energies. The 565 keV normalization appears particularly promising in this regard, and causes a less severe under-response at energies above ~1 MeV, though the 144 keV normalization provides a smaller over-response at keV energies; however, it is remarked that the keV-range is less critical than the MeV-range for radiological protection, as shown by the magnitude of the conversion coefficients. The black lines in Figure 3.19 indicate the $H^*(10)$ performance criteria currently recommended for neutron survey instruments by the IEC standard (IEC, 2014); strictly these would be inappropriate for judging the H^* performance, but it can be presumed that similarly stringent criteria would be desired for responses given in terms of the new dose quantity, so are included here for general guidance.

Note, however, that this solution is not always feasible. The intrinsic calibration cannot always be changed: even with a new calibration factor the indication of the monitor will still give the same value and recalculation of the doses is needed after the measurements.

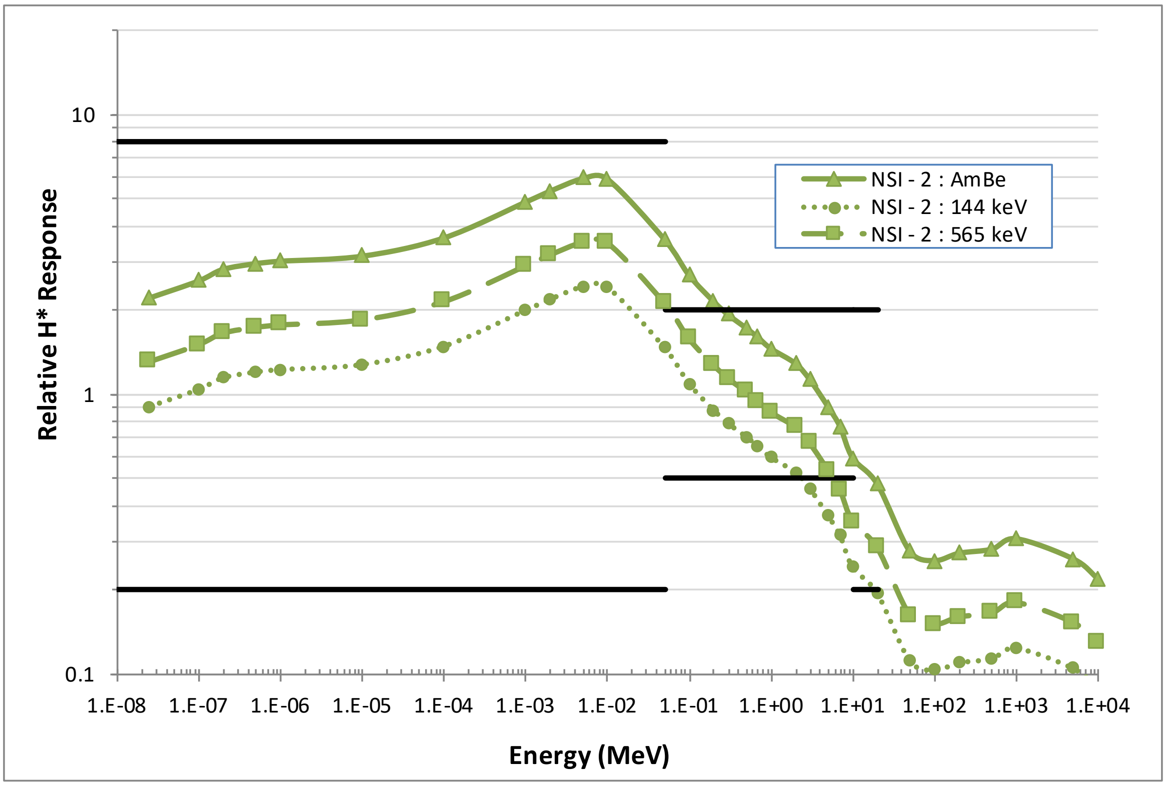

Figure 3.19 *H**response of the NSI – 2 neutron survey instrument, (re)calibrated to its Am-Be, 144 keV or 565 keV responses. The black lines indicate the *H**(10) performance criteria currently recommended by the IEC standard (IEC, 2014).

Figure 3.19 demonstrates that recalibration of an instrument may provide a simple means of improving its energy-dependent response characteristics for the new quantities. However, routine testing of devices by their manufacturers or at calibration laboratories relies on the ready availability of appropriate sources. In that regard, it is remarked that the best source to recalibrate against in terms of optimizing the energy-response may not be accessible to laboratories for routine use, or even easily to all Secondary or Primary standards metrology laboratories. The recalibration to 144 or 565 keV neutrons was considered because these are quasi-monoenergetic calibration fields that can be provided by some Primary Standards Laboratories (e.g. those of France at IRSN, the UK at NPL, Germany at PTB, and Japan at NMIJ). However, there are obvious cost and convenience implications if these options are chosen. Monoenergetic neutron fields are not usually considered for routine calibration, unless instruments are going to be used in these types of fields. Their value is as test facilities where the response functions of devices can be measured. In that regard, the current use of 'common' radionuclide sources, such as ^{241}Am-Be or ^{252}Cf for neutrons, ^{137}Cs or ^{60}Co for photons, ^{90}Sr/^{90}Y for betas, etc., for regular and routine check calibrations is clearly preferable. Alternatively, calibration in a simulated workplace field might also be a desirable option.

The above observation leads to the suggestion that a better option could be to retain use of the current calibration sources, but to apply a constant scaling factor with a value that is either <1 to correct for a consistent over-response, or >1 to correct for a consistent under-response. This scaling factor could be chosen freely, in order to provide the optimum response characteristics for a given instrument or dosemeter. Alternatively, a more metrological approach might be envisaged in which the value of the scaling factor is informed by taking the ratio of the measured responses at the routine calibration energy and the optimum calibration energy. For instrument NSI–2, for instance, the scheme could operate by calibrating to ^{241}Am-Be, but using the ratio of this with the 565 keV response to determine the scaling factor: the expensive exposure to the 565 keV field need then only be performed once, during initial type-testing of the device, with future calibrations then checked routinely against the comparatively cheaper ^{241}Am-Be source exposure.

Although in some cases recalibration may improve relative performances overall, it obviously will not improve the energy dependence of an instrument's response and so cannot alone solve all of the limitations that would be introduced for the current designs upon adopting the new dose quantities. For example, recalibration of NSI–2 clearly improves its overall performance for H^*, but such an approach is only providing a partial solution: the recalibration to 144 or 565 keV would worsen the under-responses at very high energies (above ~50 MeV) that are caused by the change to the dose quantities (cf. Figure 3.17).

Of course, the above under-response at high energies will not be a problem in most workplace neutron fields, such as in the nuclear industry where neutron energies rarely exceed ~20 MeV. The good performance of the recalibrated NSI–2 at energies below 20 MeV may therefore be adequate in most cases, which leads to the suggestion that one way to circumvent the issue could be to restrict the scope of its applicability from the current thermal to 10 GeV range for $H^*(10)$ to a thermal to 20 MeV range for H^*. Nevertheless, it would clearly be unfortunate to have to reduce the scope of any device, and probably unpalatable for its manufacturer

The above approaches combine a recalibration with a restriction of the devices' intended scope. The latter restriction is an example of a revision of dosemeter and instrument usage, which will be discussed further later.

3.5.1.2 Alternative calibration protocol

A recalibration or re-normalisation approach might also be appropriate for the LiF:Mg,Cu,P finger stall dosemeter shown in Figure 3.7: the fluence to $D_{\text{p local skin, Rod}}$ and $H_p(0.07)$ conversion coefficients are fairly similar at low energies but diverge at higher energies (Figure 3.1), so routine calibration of the dosemeter to ^{137}Cs leads to the emergence of a large and fairly consistent under-response to $D_{\text{p local skin, Rod}}$ across the 10 keV to 300 keV energy range. An analogous result was observed for the 'skin element' of the LiF:Mg,Cu,P whole-body dosemeter, and was caused similarly. The performance may potentially be improved by recalibrating the dosemeter to its response to, say, 50 keV or 60 keV photons, or for example the N-60 or N-80 Narrow Series fields (which have mean energies of 48 keV and 65 keV respectively), while also restricting the range of its applicability to use only in fields for which photon sources higher in energy than ~300 keV are known not to be present. Although, again, it would be undesirable to have to reduce the scope of the dosemeter, such an exclusion may generally be considered acceptable in many circumstances because high-energy photon sources are deeply penetrating, and so are typically of more concern for whole body dosimetry than skin doses, with whole body dosemeters accordingly worn by workers exposed to them to monitor $H_p(10)$ or H_p.

The large divergence of the $H_p(0.07)$ and $D_{\text{p local skin}}$ conversion coefficients for ^{137}Cs exposures is caused by the assumption of secondary charged particle equilibrium (kerma approximation) being used in the calculation of the current operational dose quantities, but not for the new quantities. However, ICRU do also provide appendicized data for photons for the new quantities that were calculated using the kerma approximation (ICRU, 2020). Indeed, and as discussed in Section 3.2.0, ICRU appears to endorse these alternative CPE-derived data for calibrating photon dosemeters and instruments, although the intended scope and limitations of that proposal are not discussed further in Report 95, nor are the envisaged purposes of the recommended non-CPE data. One option for improving the relative $D_{\mathrm{p\ local\ skin}}$ response of the LiF:Mg,Cu,P dosemeters (Figures 3.7 and 3.9) might therefore be to apply these alternative conversion coefficients during the calibration stage of its characterization.

Figure 3.20 compares the $H_{\mathrm{p}}(0.07)$ and $D^{kerma}_{\mathrm{p\ local\ skin,\ Rod}}$ conversion coefficients, and shows the $H_{\mathrm{p}}(0.07)$ or $D^{kerma}_{\mathrm{p\ local\ skin,\ Rod}}$ responses of the LiF:Mg,Cu,P finger stall dosemeter to photons at normal incidence, relative to the $H_{\mathrm{p}}(0.07)$ or $D^{kerma}_{\mathrm{p\ local\ skin,\ Rod}}$ response (as appropriate) to the ^{137}Cs field. A comparison of the $H_{\mathrm{p}}(0.07)$ and $D^{kerma}_{\mathrm{p\ local\ skin,\ Slab}}$ conversion coefficients is also shown in Figure 3.20, along with the $H_{\mathrm{p}}(0.07)$ or $D^{kerma}_{\mathrm{p\ local\ skin,\ Slab}}$ responses of the ‘skin element’ of a LiF:Mg,Cu,P whole-body dosemeter to photons at normal incidence, relative to the $H_{\mathrm{p}}(0.07)$ or $D^{kerma}_{\mathrm{p\ local\ skin,\ Slab}}$ response (as appropriate) to the ^{137}Cs field. Response data for the BeO ring extremity dosemeter, and ‘skin element’ of the BeO whole-body dosemeter, are also provided in Figure 3.20, for comparison against Figures 3.7 and 3.9; data are normalized using the ISO Narrow Series N-300 X-ray field at 0°.

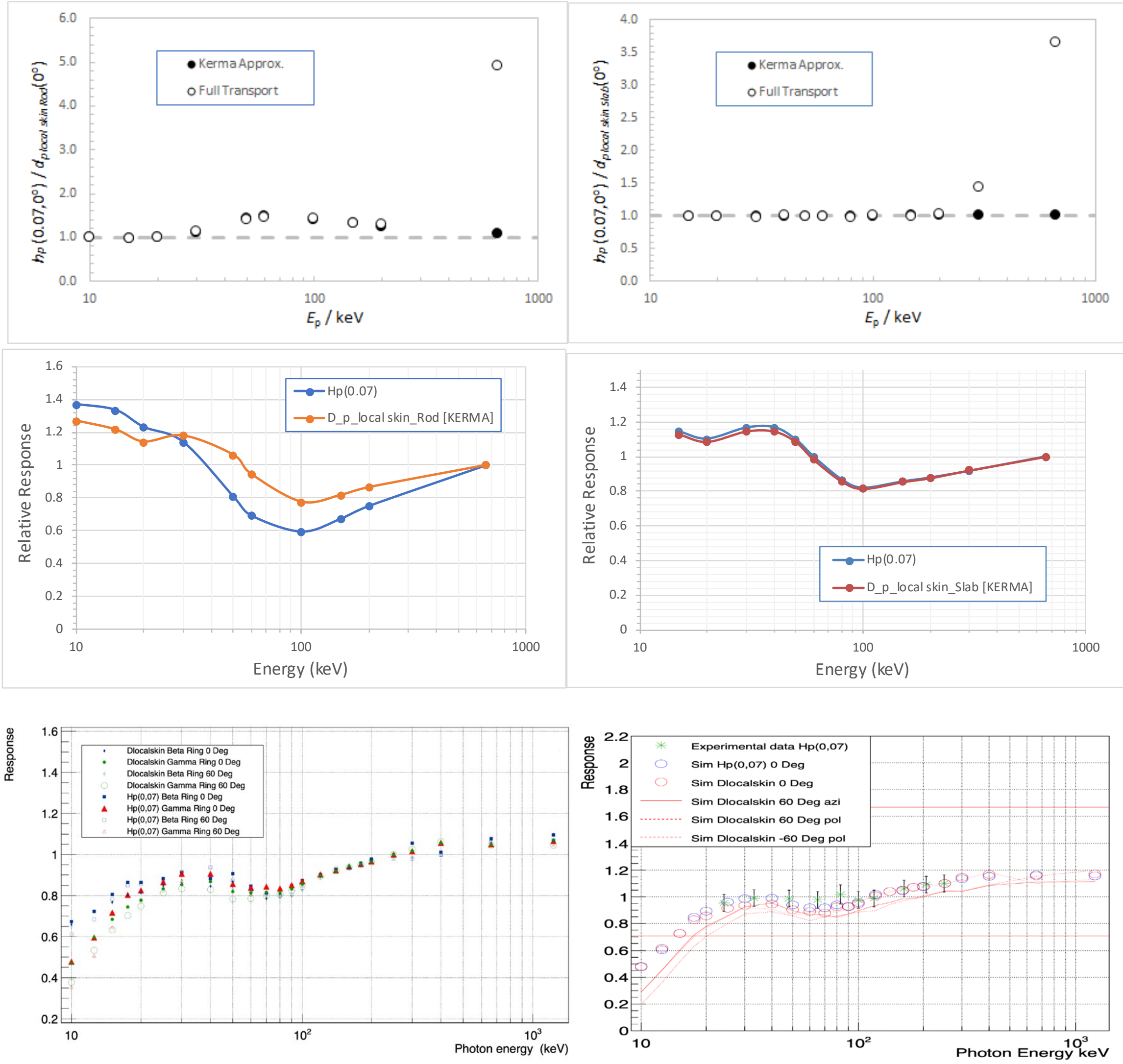

Figure 3.20 (Top left) Ratios of rod-phantom $h_p(0.07)$ to $d_{p\text{ local skin, Rod}}$ and $d^{kerma}_{p\text{ local skin, Rod}}$ for photons. (Top right) Ratios of slab-phantom $h_p(0.07)$ to $d_{p\text{ local skin, Slab}}$ and $d^{kerma}_{p\text{ local skin, Slab}}$ for photons. (Middle left) Responses of a LiF:Mg,Cu,P finger-stall dosemeter for photons under presumed conditions of kerma equilibrium. (Middle right*)* Responses of the 'skin element' of a LiF:Mg,Cu,P whole-body dosemeter for photons under presumed conditions of kerma equilibrium. (Bottom left) Responses of a BeO ring extremity dosemeter for photons under presumed conditions of kerma equilibrium (Bottom right*)* Responses of the 'skin element' of a BeO whole-body dosemeter for photons under presumed conditions of kerma equilibrium.

Figure 3.20 shows that the use of the kerma approximation for the characterization of dosemeters, and realised by the inclusion of appropriate thicknesses of build-up during calibration exposures in metrology laboratories, would provide a partial solution to some of the energy-dependent problems exhibited in their relative responses for photons (Figures 3.7 and 3.9). However, discrepancies between expected and actual performances could then arise if monitored workers were occupationally exposed to photon fields in which secondary charged particle equilibrium (CPE) did not exist, though any inherent filtration within the dosemeter itself could potentially mitigate against this to some extent. For example, a dosemeter originally calibrated to ^{137}Cs using $D^{kerma}_{\mathrm{p\ local\ skin}}$ would then over-respond to $D_{\mathrm{p\ local\ skin}}$ in such ^{137}Cs workplace exposures. Of course, similar problems may also exist with the current operational quantities, the conversion coefficients for which were also calculated under the assumption of CPE, with near-contact photon exposures being an obvious example for $H_{\mathrm{p}}(0.07)$.

As the energy of the photon source is increased, the maximum range of secondary electrons that it can produce also increases, so the likelihood that CPE exists at the location of the individual and dosemeter reduces. For unshielded sources in air, large source-dosemeter distances may therefore be required to ensure CPE: for ^{137}Cs exposures, for instance, over 2 m of air is required (ICRU, 1984). Such distances may or may not be present during routine workplace exposures to a given source, obviously depending on the environment and the nature of the work performed. This relationship would affect skin dosimetry in several contrasting ways. On one hand, it could be suggested that insufficient build-up would not be a major problem for extremity dosimetry, because the focus for this often tends to be towards low-energy photon sources. On the other hand, finger stall dosemeters are typically worn when individuals are close to sources or directly handling them, and these short distances may still be insufficient to induce CPE even for some lower-energy photon sources (Behrens, R *et al*, 2009). Of course, the values of $D_{\mathrm{p\ local\ skin}}$ and $D^{kerma}_{\mathrm{p\ local\ skin}}$ are broadly consistent at energies below ~few 100 keV, so this latter observation may not be an issue in practice (Cf. Figures 3.7, 3.9 and 3.20). Conversely, lack of CPE may be more problematic for the higher energy sources that are more typically associated with whole body exposures and monitored by the skin elements of whole-body dosemeters. Under such circumstances the skin element of the whole-body dosemeter could essentially over-estimate the true dose, noting that the same outcome also applied to estimates of $H_{\mathrm{p}}(0.07)$ in cases where CPE was not achieved. Nevertheless, it is remarked that the dosemeter would still be performing conservatively in this scenario, so importantly would not lead to under-assessments of the radiological risk.

A mixed approach may ultimately be necessary for skin dosimetry for photons, where for instance the dosemeter is characterized in terms of its response to $D_{\mathrm{p\ local\ skin}}$ (by applying conversion coefficients derived using full coupled photon-electron transport), but then normalized to its calibration response, e.g. to ^{137}Cs or N-300 or even at a lower energy, given in terms of $D^{kerma}_{\mathrm{p\ local\ skin}}$ (obtained using conversion coefficients derived under the assumption of kerma equilibrium). Given that the divergence between the two sets of conversion coefficients only becomes significant at higher energies, the responses of the LiF:Mg,Cu,P and BeO extremity and whole-body dosemeters calibrated using such a scheme would effectively be identical to those shown in Figure 3.20. This indicates that the effects of the changes to these operational dose quantities could largely be mitigated for photons, and may not greatly affect skin dosimetry if the kerma-approximation conversion coefficients are used.

The impacts on the calibration of dosemeters and instruments resulting from the revised operational dose quantities are discussed more fully in Chapter 5.

3.5.2 Redesigns of the dosemeters and instruments

Section 3.5.1.1 highlighted a way in which a simple modification to the calibration procedure was able to provide a global shift in the response of an instrument or dosemeter. Such an approach would be able to 'correct' the response when a broadly constant, energy-independent difference exists in the values of the old and new operational dose quantities. However, it is clear from Figures 3.7 to 3.18 that, in many cases, significant energy-dependent differences in response would be introduced by the adoption of the new quantities, and these could not be resolved simply by applying a constant multiplication factor. In such cases, modification of the dosemeter or instrument itself may be required. For multi-filter personal dosemeters, adjustment of the dose assessment algorithms may remove or reduce the need for physical modifications.

Modification of a dosemeter or instrument response could be achieved by increasing or decreasing the thickness of a particular part of its construction, in order to increase or decrease the degree to which that feature attenuates or boosts the detected radiation field within a particular energy range; the end goal of such a change would be to help flatten the energy-dependence of the response characteristics. The use of alternative materials, with alternative radiation absorbing, attenuating, or boosting powers, may achieve the same end. For example, for photon dosemeters and instruments, the replacement by materials of higher / lower Z could be used to lower / raise an over- /under-response, with consideration of different K-edge energies also potentially used to control different energy-dependent features of their response characteristics. For neutrons, choosing materials with greater or lesser moderating power (e.g. varying its hydrogenous content) or incorporating materials with greater or lesser neutron-absorbing properties (e.g. raising / lowering boron-10 or lithium-6 content, etc.), for example, could similarly be used to control different aspects of the response of the dosemeter or instrument.

From a manufacturer's perspective, the preferred approach would be to modify the device by as little as possible, endeavouring to improve its response characteristics but not to embark upon an expensive full restructure; even then, there would still inevitably be outlay from material costs and associated repetitions of type-testing, etc, as well as the initial research time required to complete the redesign process itself. To that end, the optimum approach might naturally be to look for simple solutions, where small change / high impact amendments could be made to overcome various deficits in the response characteristics. The simplest such solutions might be those that may be retrofitted to existing designs, without requiring major restructuring or retooling. Examples of this could be the replacement of some feature of the dosemeter or instrument, of given dimensions and material, with an identically shaped feature but of an alternative material that had better / worse attenuation properties for a given radiation field and energy, depending on whether the intended aim were to suppress an over- or under-response, respectively. In such a case, it may conceivably be an easy retrofit task to simply open the dosemeter or instrument and swap the old material for the new.

As an example, consider the H_p response of the LiF:Mg,Cu,P whole-body dosemeter shown in Figure 3.10. The dosemeter features attenuating material in front of the LiF:Mg,Cu,P body element that comprises a polytetrafluoroethylene (PTFE) filter covered by polypropylene (PP), which together are equivalent to ~10 mm of tissue as required for the intended purpose of measuring $H_p(10)$ (Eakins *et al*, 2007). However, Figure 3.10 indicates that this design of dosemeter would over-respond significantly to photons in the ~20-50 keV range, with a large H_p dose exhibited. Above ~100 keV, however, the performance of the TLD is relatively unaffected by the change from $H_p(10)$ to H_p. The task is therefore to adapt the design such that the over-response is supressed in the ~20-50 keV range, but left relatively unchanged at other energies.

The PTFE filter is cylindrical and fits tightly into a 4.3 mm deep, 18 mm diameter recess in the TLD holder, which is constructed from injection-moulded PP. Modifying the shape and material of the PP holder would be relatively expensive, requiring new tooling and manufacturing processes. However, there is more scope for adapting the filter material contained within it, which would be comparatively easy to implement if the proposed modification could still be contained within the existing recess in the PP. In particular, replacing some or all of the PTFE filter with a material that has a greater effective *Z* and/or density might be expected to supress the over-response in the low-energy (i.e. photoelectric) range, whilst leaving the overall thickness of the filter comparatively unchanged and hence still able to fit within the current holder.

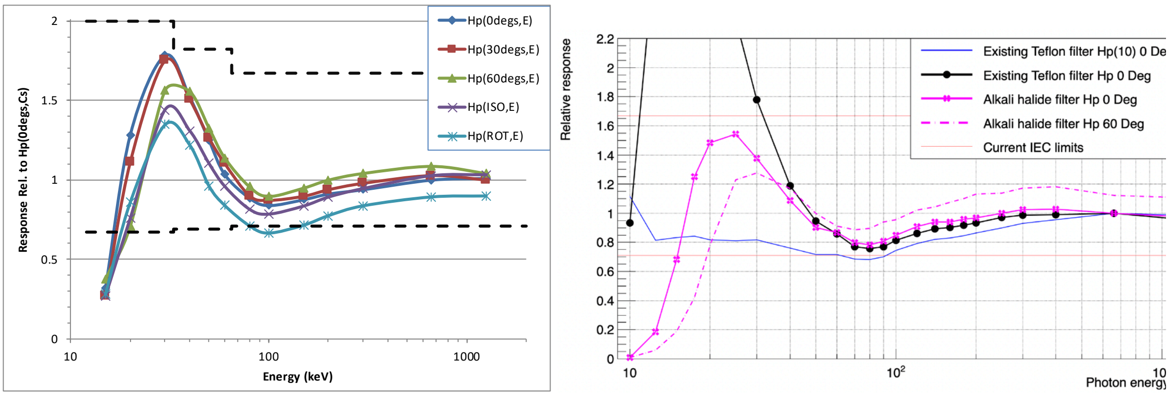

Figure 3.21 (Left) Photon $H_p(\varphi)$ response of the redesigned TLD as a function of energy and angle, relative to its ^{137}Cs response at normal incidence. Also shown are the limits recommended by the IEC for personal dose equivalent (dashed lines). [Eakins *et al*, 2019] (Right) Photon $H_p(10,\varphi)$ and $H_p(\varphi)$ responses of a current / redesigned BeO two-element whole-body dosemeter as a function of energy and angle, relative to its ^{137}Cs responses at normal incidence.

Figure 3.21 shows the H_p responses of an adapted TLD that features a 1.5 mm thick, 18 mm diameter aluminium cylinder located between the PP and the PTFE cylinder, the thickness of which has been correspondingly reduced by 1.5 mm (Eakins *et al*, 2019); data are shown for several different exposure geometries, and are given relative to the ^{137}Cs response for H_p at normal incidence. It is clear that the inclusion of the aluminium disk reduces the previous over-response (Figure 3.10) within the ~20-50 keV range to within acceptable levels, without detriment to the performance at higher-energies. Indeed, the redesigned TLD complies with the limits recommended by the current IEC standard across the entire energy range apart from at 15 keV, notwithstanding that these criteria are defined in terms of personal dose equivalent rather than personal dose. Moreover, it can be shown that no significant loss of sensitivity would be incurred by making this change. Perhaps more importantly, however, it would also be easy to obtain aluminium and reduced-thickness PTFE cylinders of the required dimensions. A relatively cost-effective solution is thus achieved, avoiding an expensive redesign process involving a complete overhaul of the dosimetry system.

Of course, it is noted that even a comparatively cheap option such as the above would still incur associated costs to the dosimetry services, with potentially very many thousands of dosemeters needing to be retrofitted. A minority of the costs – in particular, research and development costs – can be spread over a period of a few years. But whilst it could be argued that some of this expense could be reduced by rolling out the new design gradually during routine wear-and-tear repair or replacement of devices, in many cases this will be impractical.

- Retro-fitting may not be practical, e.g. if removal of the existing filters damages the holder or filter pack. It is likely to be more reliable and less costly overall to simply replace the old-style holder or pack with the new-style ones.

- For both instruments and personal dosemeters there would be a period when old and new quantities are being used side by side. This could lead to operational confusion.
- For personal dosemeters, there are serious logistical drawbacks to having "old-type" and "new-type" dosemeters in circulation at the same time, making the service less efficient.
- National legislation and national dose registries would need to allow for both old and new quantities being used.
- The roll-out of the modified instruments or dosemeters would need to be co-ordinated with changes to national regulation and recommendations.

For operational reasons it is inadvisable to extend the roll-out period any more than is absolutely necessary. Cost savings from, for example, not having to maintain old instruments or not having to replace lost personal dosemeters, will therefore be small.

Figure 3.21 also shows the outcome of a similar redesign process for the BeO dosemeter shown in Figure 3.10, where its current PTFE filter, which was incorporated so that its response matches the requirements of $H_p(10)$, has now been replaced by an alternative, alkali-halide filter that is intended to provide a better H_p response. The photon responses of the current design to $H_p(10)$ and of the modified design to H_p, are shown normalized to their respective ^{137}Cs exposures at 0° incidence. The H_p response is greatly improved by the modification. However, and similarly to the adapted LiF:Mg,Cu,P TLD, it is clear that a large under-response persists at photon energies below ~20 keV. Moreover, it is remarked that whilst a similar improvement in the overall H_p response can be achieved using other filter materials, e.g. Al with a different thickness, the under response at the lowest energies cannot be improved with other materials (Hoedlmoser *et al*, 2020). This limitation could prove problematic in dosimetry for radiology exposures, for instance, for which low-energy photons can be particularly important.

It is obvious that the examples given above are just two cases, and clearly would not be appropriate for every other type of dosemeter or instrument, or even for other types of passive dosemeter intended to measure for H_p for photons. The redesign process for a given dosemeter or instrument would naturally be highly bespoke, and it is not possible to provide exhaustive discussion of the topic here. Nevertheless, the overall approach that manufacturers might follow would probably be fairly common:

- Consider which materials or dimensions could most easily be changed, in order to 'solve' a particular energy-dependent over- or under-response to a given dose quantity in a given field;
- Replace those features with alternatives of greater or lesser attenuating power, as appropriate;
- Carefully ensure that the responses for other energies, angles or radiation types are not unduly affected.

Most probably, this process would be achieved by a campaign of extensive and iterative Monte Carlo modelling, with many different trial designs considered and explored, and supported by supplementary measurements. The final redesign would then be subject to rigorous type-testing against accepted performance criteria (see Chapter 7).

It is remarked that some required improvements to a dosemeter or instrument's response may be harder to achieve through this simple retrofitting approach. For example, Figure 3.19 showed the H^* response of the NSI–2 neutron survey instrument that had been recalibrated using 565 keV. This recalibration was found to be successful in improving the performance in general, but a small over-response still existed at the lowest energies along with a significant under-response at the highest energies, which was greatly exacerbated by the change from $H^*(10)$ to H^*; the low-energy over-response may be removed by recalibrating to 144 keV, but this led to an even worse performance at the highest energies, making it a less desirable option overall. It has been shown elsewhere that a cheap and simple retrofit solution[4] (Eakins *et al*, 2018) may easily be implemented to remove the over-response to H^* at thermal energies. However, resolving the problems at the highest energies would prove more challenging. One potential solution to this could be to increase the thickness of a lead layer within the instrument, which boosts the response to very high energy neutrons via the (n,2n) reaction. However, this modification would come with a large penalty: lead is dense, and neutron survey instruments are typically already heavy. Likewise, increasing the moderating mass could also be an option, though this would be to the detriment of the response at other energies, which could be supressed too much, and would again also be associated with weight increases that degrade the portability and routine usability of the device. A fuller discussion of the impacts of the changes to the dose quantities to neutron measurements and instruments at high energies is summarized elsewhere (Pozzi *et al*, 2019). Of course, significant energy-dependencies are typically exhibited by neutron survey instruments anyhow, and even the best designs only provide 'reasonable' estimates of $H^*(10)$ currently; it should be remarked, therefore, that the negative impacts of the proposed change to H^* may generally be interpreted as worsening an existing problem rather than creating a new one.

Overall, the suggestion is that not every under- or over-response introduced by the change to the dose quantities for a given dosemeter or instrument could be resolved simply by a small tweak to its design, or by a simple retrofit solution. A further example of this could be the track-etch whole body neutron dosemeter shown in Figure 3.15: although the addition of a little more filtration could conceivably prove to be a relatively easy method for reducing the over-response to H_p at low-energies, supressing the large over-response at ~1 MeV may be more challenging, and it is not at all obvious how the strong angle-dependence introduced by the change from $H_p(10)$ to H_p could be reconciled (Tanner *et al*, 2018).

Instead, full redesign campaigns may be required, and even then it is likely that some difficulties would still remain. Amongst other factors, this latter expectation is due to the inevitable and inherent differences in shape and size between dosemeters / instruments and the anthropomorphic phantoms in which the dose quantities are defined, as well as the difficulty in extrapolating the effects of the aggregate doses distributed in tissues and organs across that extended body from the measured dose at a single point. Of course, many of those limitations were also equally intractable for the old dose quantities, and indeed in some cases were even more pronounced for the dosemeters and instruments designed to respond in terms of them.

The effectiveness of any re-optimization or redesign campaign would be judged against the performance criteria stipulated for dosemeters and instruments (e.g. (IEC, 2012) for photon dosemeters, (IEC, 2014) for neutron survey instruments etc.). However, it is remarked that those recommendations would, in time, also preferably be updated to better reflect the requirements of the proposed dose quantities. Questions then remain of what types of performance would be expected from dosemeters and instruments, what response characteristics would be required or

[4] NSI–2 contains air-filled guides that channel thermal neutrons through its moderating mass to the central detector, thereby increasing the low-energy $H^*(10)$ response often common to neutron survey instruments, without undesirably reducing the intermediate- and high-energy $H^*(10)$ responses. These guides are capped by short, removeable polyethylene plugs. Replacing the plugs with alternatives of greater depth was shown to improve the low-energy H^* response, without penalty at other energies [Eakins *et al*, 2018].

considered acceptable, and indeed what stipulations might be recommended on exactly what does or does not need to be measured.

Regarding the last of those, it may reasonably be argued that if an operational dose quantity is defined and conversion coefficients calculated for it for a given set of conditions, then it ought to be measurable. On the other hand, in some circumstances this task might be extremely difficult to accomplish in practice, and may perhaps only achieve diminishingly small returns in terms of radiological risk assessments; the potential need for photon-electron dosemeters to measure the H_p response to electrons of arbitrarily low energies is an example of this (cf. Figure 3.13). Similarly, a comparison of $H_p(10,90°)$ or $H_p(10,180°)$ against $H_p(90°)$ and $H_p(180°)$ provides an obvious example of the conceptual superiority of the new quantities over the old in terms of quantifying the true dose to an individual, but they will be equally hard to measure accurately by a single dosemeter worn on the front of the body.

The issue of how standards agencies might formulate new recommendations in response to the changes proposed by ICRU is discussed in Chapter 7. For now, it is remarked that the new quantities might conceivably allow for new opportunities in dosimetry, and that the redesign processes may potentially lead to solutions that are an improvement on the options currently available.

3.5.3 Revisions of dosemeter and instrument usage

Hybrid approaches, involving recalibrations and/or restricted ranges of intended scope and/or retrofit redesigns, may offer full or partial improvement to the performances of existing dosemeters and instruments when required to respond in terms of the new dose quantities. The first and third of these approaches probably involve some expense, of greater or lesser extent. The second includes options such as limiting the energy range in which the device is used, but it would obviously be unfortunate to have to restrict the scope of any given dosemeter or instrument more stringently than its current limitations, and this outcome would clearly be an undesirable choice for stakeholders such as their manufacturers.

A more positive approach might therefore be to explore possible modifications to the way in which the device is used or read out, with the hope of finding ways in which the problems could be avoided. Such a possibility might be promising for systems that use multiple sensitive regions to detect radiation, each located differently or surrounded by materials of diiffering attenuation properties. In such systems, the overall dose estimate is typically obtained by combining the separate results according to a specific dose reconstruction algorithm. Modifications to these algorithms might allow improved estimates of the new dose quantities, with perhaps the various elements given different weightings from those used currently to estimate the existing dose quantities.

Figure 3.22 shows the impact of changing the dose reconstruction algorithm for the BeO whole-body dosemeter discussed previously (Figure 3.10). The photon responses using the current single-element algorithm for $H_p(10)$, and using a re-optimized non-linear two-element algorithm for H_p, are shown normalized to their respective ^{137}Cs exposures at 0°. The specifics of the dose reconstruction algorithm are commercially confidential (Hoedlmoser *et al*, 2020), so cannot be detailed further here, but it is evident that a re-optimized function provides a promising solution to the over-response exhibited when the current $H_p(10)$ algorithm is used for H_p assessments. However, it is clear that the dosemeter still under-responds greatly at energies below ~20 keV, which is a feature that was also exhibited by the redesigned BeO dosemeter (and LiF:Mg,Cu,P dosemeter; Figure 3.21). Nevertheless, changing the dose reconstruction algorithm would be a much more cost-effective solution than modifying the dosemeter itself, even if that redesign were just a simple retrofit replacement of a filter, so may be considered the preferred option by the manufacturer. However, modifications of a dose reconstruction algorithm to incorporate additional elements would be likely to come with the penalty of increased measurement uncertainties. For example, if a dosemeter can currently determine $H_p(10)$ using just one element but requires two elements to determine H_p via some combinatory algorithm, then the measurement uncertainty on the estimate of 'whole body dose' might be expected to increase by the order of √2. Moreover, it should be noted that moving from a linear single-element algorithm to a non-linear two-element algorithm could introduce additional measurement uncertainty, and somewhat degrade the performance of the badge.

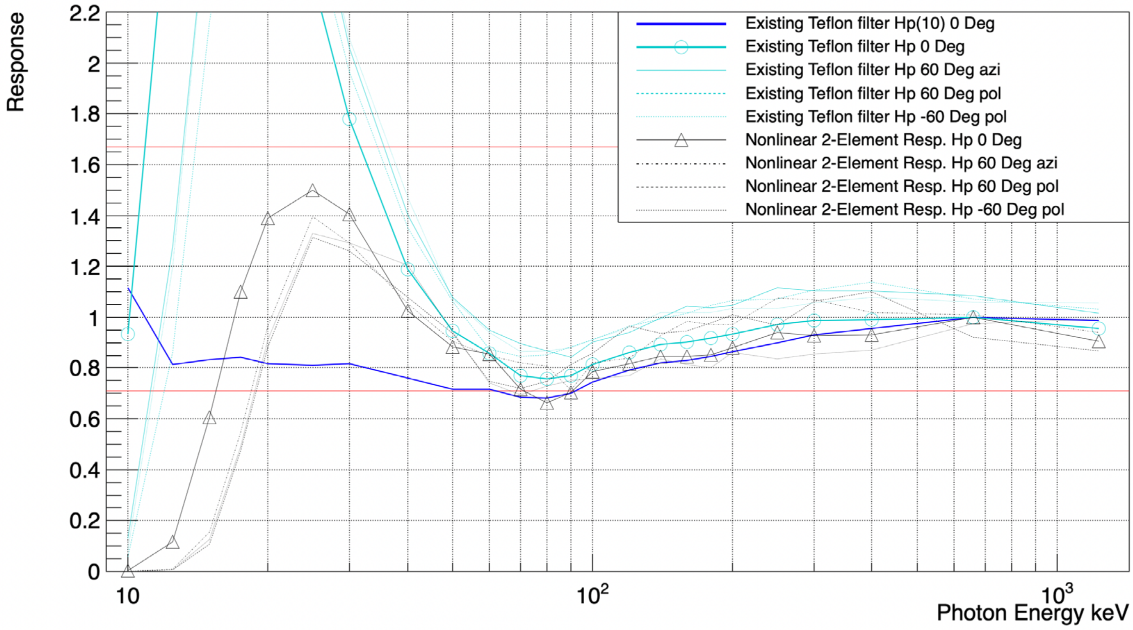

Figure 3.22 Photon $H_p(10,\varphi)$ and $H_p(\varphi)$ responses of a BeO dosemeter using current / re-optimized dose reconstruction algorithms as a function of energy and angle, relative to its ^{137}Cs responses at normal incidence.

3.5.4 Computational On-line Dosimetry

Recent developments have shown the feasibility of making a novel type of dosimetry possible (Abdelrahman *et al*, 2020a, Abdelrahman *et al*, 2020b, Almén *et al*, 2021, Eakins *et al*, 2021). This proposal would improve personal dosimetry by using an innovative approach: the development of an online dosimetry application based on computer simulations. With the use of modern technology such as personal tracking devices, flexible individualized phantoms and fast simulation codes, the aim is to perform personal dosimetry purely by simulations, thereby avoiding the need for physical dosemeters. The availability of the proposed online personal dosimetry system could therefore overcome some of the problems that arise from the use of current passive and active dosemeters. Such limitations include the uncertainty in assessing neutron and photon doses when part of the body is shielded, the delay in calculating the doses, and the situation where workers position dosemeters incorrectly or neglect to wear them.

As all doses are calculated rather than measured, another advantage is that these simulations can immediately use effective doses and organ doses, which are superior as estimators of true radiological risk to individuals. It would thus remove the need for operational quantities and would hence not be affected by the changes proposed in ICRU Report 95. The initiators of the research into online dosimetry anticipate that the methods might be available on the same timescales as are likely for the implementation of these new operational quantities into legislation.

3.6 Chapter summary and conclusions

- The changes to the definitions of the operational dose quantities will alter the response characteristics of the instruments and dosemeters that are used for their monitoring. Since existing devices are optimised for the current operational quantities, it is most likely that their performance, if unmodified, will be worse in terms of the new ones.
- For an ideal dosemeter or instrument the impact will be dictated by the changes to the values of the conversion coefficients, and can be quantified for a particular radiation exposure at a given energy or angle by the ratio of the old and new conversion coefficients for that field (Figures 3.1 – 3.6). The ratios of the old and new values for the routine calibration fields will also affect these analyses.
- Real dosemeters or instruments, however, exhibit energy- and angle-dependences, so that their relative responses diverge from unity. These departures from a flat response may be caused by a number of factors, and may be common to all dosemeters or instruments of a given type, or else unique to a specific design.
- Therefore, consideration only of the changes in the conversion coefficients is not sufficient to predict the performance of a device in terms of the new quantities. A change in the value of the conversion coefficient for a particular radiation exposure at a given energy or angle could result either in a fortunate mitigation of a current over- or under-response for that exposure, or else to an unfortunate worsening of a current over- or under-response.
- Figures 3.7 – 3.18 demonstrate that although the responses of a number of devices are worsened, this is sometimes not the case. Moreover, the responses of devices with a common purpose but different design will not all improve or degrade equally. The overall impact of the change will therefore be design-specific, and will need to be considered on a case-by-case basis.
- It is noted that improvements of the response in some fields may not necessarily be balanced by degradations in others. For some photon dosemeters for example, difficulties in measuring H_p at low energies, which can be particularly important for radiology exposures, might in those cases outweigh improvements elsewhere.
- Some of the negative impacts will be possible to mitigate at some energies and angles, whilst others will be more intractable and may make particular types of device unusable.
- For photon exposures, including all calibration and type-testing, application of the alternative “kerma-approximation” conversion coefficients based on the assumption of secondary charged particle equilibrium (CPE)[5] is recommended. (See also the discussions in Chapter 5 below.) For extremity dosemeters in particular, there is no choice but to use the kerma-approximation set. This approach would also resolve some of the other issues discussed above.
- The ICRU report states that the kerma-approximation conversion coefficients may be used for calibration purposes, but does not elaborate on that point or provide any discussion or

[5] ICRU 95, Appendix A.5.

clarification for when the recommended non-CPE data ought to be used instead. This doubling of datasets, and the associated lack of detailed explanation, could lead to confusion within the dosimetry community.

- The simplest means to mitigate some effects may be by recalibrating the dosemeter or instrument using an alternative source or by applying a calibration factor (Figure 3.19). For the former, the ready availability of any alternative source needs to be considered.
- For multiple-element systems, modifications to the dose evaluation algorithm may also be an option (Figures 3.22), though these could increase measurement uncertainties. Work remains to be done in these areas.
- Some improvement may be afforded by simple retrofit redesigns of current instruments, such as by adding or removing filtration, perhaps by using thicker/thinner or alternative materials (Figures 3.21). Although obviously more attractive than full redesign and replacement campaigns, such modifications would still attract significant costs. Retrofitting is unlikely to be a practical option for passive dosemeter holders or filter packs.
- Although in some cases the expense could be mitigated by performing the retrofitting gradually during routine wear-and-tear repair or replacement, practical considerations mean that the changeover period should not be more than a few months.
- Changes to the way in which dosemeters and instruments are routinely used may also offer a partial solution in some circumstances, such as restrictions to their energy range or scope of applicability. Clearly, this choice would be undesirable to users, manufacturers and other stakeholders.
- For many dosemeters or instruments, a combination of the above mitigation approaches might be required to resolve different radiation type-, energy-, or angle-specific problems.
- In some cases, however, complete redesign of the dosimetry system will be needed to better match the requirements of the new dose quantity, perhaps by developing a completely new device. The associated costs would be very significant. Even then, some limitations may still persist. For photon personal dosemeters, for instance, matching the H_p requirements across the desired full energy range may prove particularly difficult with a single element design. This issue would be further complicated in mixed fields.
- For aircraft crew, the ICRU recommendations could be taken to mean that the TEPC should no longer be used, because it cannot measure H^*. But, following the clearly demonstrated ability to estimate effective dose using this procedure, the TEPC may be kept as a reference instrument, although new calibration procedures are advisable.

4. Impact on RP Practices

The effect of the implementation of the new quantities presented in the ICRU/ICRP report on radiation protection practices must be considered for a certain number of domains and points of view because it depends on several parameters, some very technical, others more organizational. This section attempts to list the areas of activity and radiation protection practices that could be affected by the changes, and to identify the impact that this would have on current practices in these domains, as well as the associated open questions.

4.1 Worker dose monitoring and specific exposure situations

4.1.1 Photon exposures

Conceptually, the new operational quantities are in theory better suited to assess effective dose. However, with this change, the measured dose values for occupationally exposed workers will change. Even if, in many cases these values do not change dramatically, for exposure situations involving low-energy X-rays, neutrons and high-energy particles, it is quite obvious that the new measured values will be different from those of the past. This could lead to different approaches to radiation protection in these fields.

As evident from Figure 3.3, the new quantities could imply a decrease by a factor of between 2 and 6 for whole body doses received in the low energy photon domain, that is to say below 50 keV). These fields concern in particular the medical sector, specifically medical diagnostic applications, which account for a very large number of workers. For effective dose, levels in this area are generally quite low compared to the limits (although annual doses of a few mSv can be recorded for a small fraction of these workers). Preliminary Monte Carlo simulations (Abdelrahman M, 2021) suggest that in a range of medical-sector workplace fields the reduction factor will be at the lower end of the expected range, i.e. around 2.

If the reduction factor were to be very marked, e.g. reducing the measured dose values by a factor of 5, there could be a temptation to weaken radiological protection measures. Therefore an effective education programme is needed to ensure that any changes in practice are properly assessed and properly understood.

The changes observed for whole body exposures are connected to the depth of 10 mm used in the definition of the current whole-body operational quantity. Weakly penetrating photons can reach 10 mm quite easily but do not reach most radiosensitive organs effectively. However, the reduction in moving from $H_p(10)$ to H_p for lower photon energies will not be replicated for skin and the eyes, because doses to those organs will still be controlled by quantities defined at depths corresponding to the basal layer of the skin and the eye lens. It is hence likely that for workplaces where low energy photons are the dominant component of the radiation field, the protection of the eye lens will become more important than determination of the whole body risk.

The new operational quantities make a direct link between these quantities and the effective dose through a series of calculated conversion coefficients. These conversion coefficients are calculated for a series of exposures (irradiation geometries). However, no guidance is given for cases of inhomogeneous exposure. This problem exists already with the present quantities, but is not addressed with the new quantities.

A typical example is the case where workers are wearing protective garments, as in interventional radiology. Parts of the organs are shielded, and the effective dose is obviously much less than without the protective garment in the same field. In practice this is solved by using either one dosemeter above or one dosemeter below the protective garment, and by using a correction factor to estimate effective dose. Another method used in many countries, and recommended by ICRP, is to use double dosimetry, one below and one above the lead apron. Here an algorithm combines both results in an approximation of the effective dose. Both dosemeters are now calibrated in $H_p(10)$, which is also not an ideal case, because some are worn above the lead apron, giving a different response in backscatter. In theory, the algorithm takes this into account if it is well designed. Still, it is known that most algorithms used now, especially the single-dosemeter algorithms, can cause large deviations from the real effective dose because of the large spread in exposure conditions (Ginjaume *et al*, 2019).

A dosemeter which will be suited for measuring the new H_p quantity, will not estimate the effective dose properly when protective garments are used. So again, some algorithm will be needed for a one or two dosemeter solution. These algorithms will need to be redetermined because of the change in theoretical response for energy and angles from the H_p dosemeters.

A better solution which fits more with the new philosophy of the new operational quantities would be to define a series of conversion coefficients for protective garments. This can be done by calculating the effective dose for different angles and energies (Saldarriaga Vargas, *et al*, 2018). Like this, one could define an "extra" operational quantity for protective garments, and specific dosemeters could be designed to measure this quantity. The advantage would be that only one dosemeter above the lead apron would be needed, without any algorithm. Of course, there are many different types of protective garments, which would lead to differences in the "reference" effective doses. Still, the differences in these reference values from different garment design and compositions would probably be a lot smaller than the spread found nowadays using the present methods and algorithms. So, it could be sufficient to use one standard protective garment situation for the definition of this extra operational quantity. In any ways, more research is needed for this special case.

There is another potential problem that will arise in case of special irradiation circumstances. Take the case of a person who is exposed to radiation only from the back, i.e. the PA irradiation condition. With the present quantities, a dosemeter needs to measure $H_p(10,180°)$. This is practically zero (at least for lower energy photons). This agrees with the response of the dosemeters mounted on the person (or a phantom), because the person's body stops most of the radiation and it cannot reach the dosemeter. The drawback was of course that the operational quantity in this case would underestimate the effective dose, because this is not zero. That is why, in current radiation protection practice, it is advised to wear the dosemeter facing the direction of the radiation, if it comes mainly from the back, or from one side. For the new quantities, the H_p will not be zero for 180° exposure (Figure 4.1), because it will closely follow E(PA). $H_p(180°)$ exceeds $H_p(0°)$ for all energies greater than 6 MeV and it is only lower by 12% for ^{60}Co, and by 17% for ^{137}Cs. Conversely, around 15 keV, $H_p(180°)$ is less than 10% of $H_p(0°)$. A personal dosemeter that is designed to measure the new operational quantities should therefore measure in theory a non-zero value also for 180°, which is practically impossible. Unless the use of two dosemeters – front and back – is considered, the solution is again to wear the dosemeter so that it faces the dominant radiation; but in this case the dosemeter itself will never be able to measure the operational quantity.

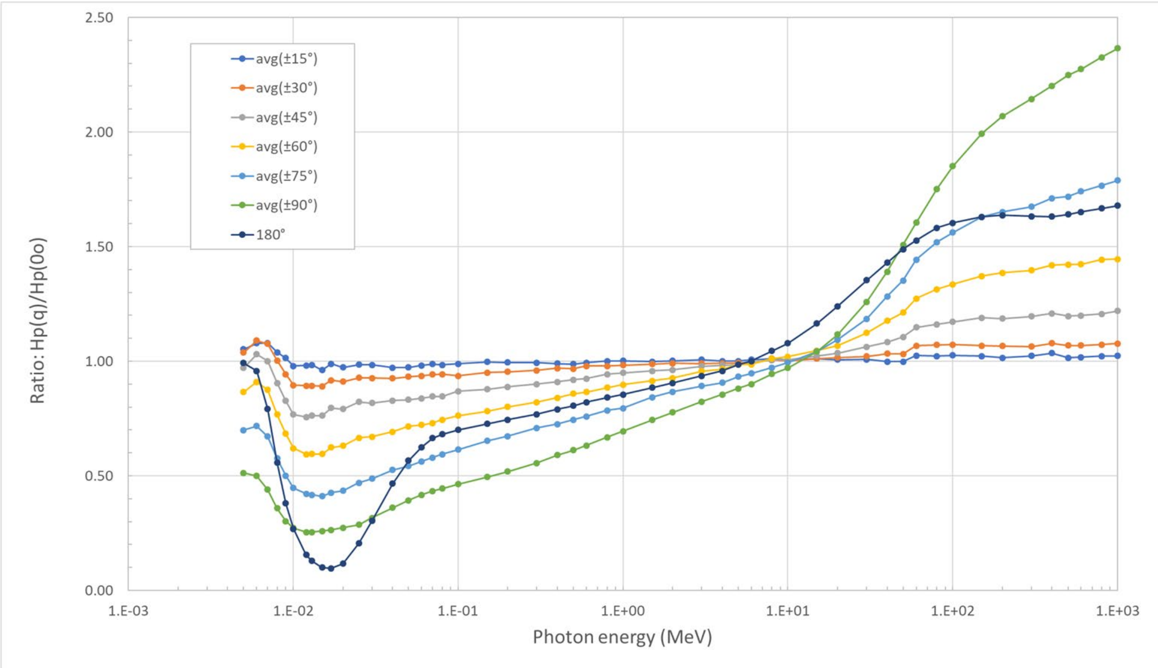

Figure 4.1 Ratio of the H_p conversion coefficient for specific angles (*q*) to that for incidence from 0°, versus photon energy.

4.1.2 Neutron exposures

The factor of up to 6 reductions in photon *personal dose* rates compared to *personal dose equivalent* rates are not seen for neutrons, anywhere across the energy range up to 20 MeV (Figure 4.2). There is a general reduction in the new quantity compared to the old for angles of incidence < 60°, though this is not true between about 2 MeV and 10 MeV. The new quantity is roughly a factor of two lower for most of the energy range, though this is not true for fast neutrons, which tend to dominate currently in terms of $H_p(10)$: the relative importance of thermal and intermediate energy neutrons will hence be reduced when the new quantities are introduced, but there will be less change for fast neutrons.

Unfortunately, the data for $H_p(10)$ that are available in ICRU Report 57 and ICRP Publication 74 are limited, with 75° being the largest angle of incidence. However, perhaps the most interesting feature of the comparison is that the data for H_p for incidence from 75° are significantly larger than those for $H_p(10)$. This mainly applies to thermal and intermediate energy neutrons, and it can be inferred that for 90° the ratio would be even higher. That is partly because the slab phantom is a poor representation of a personal dosemeter exposure on-body for 90° incidence, but also a reflection that the neutrons no longer need to reach a point 10 mm below the centre of the front face of a phantom to contribute to the operational quantity for whole body neutron exposures. The situation for angles of incidence > 90° also has to be inferred, but it is inevitable that, except for the highest energies, the *personal dose* will be much higher than *personal dose equivalent*.

In a workplace, fast neutron exposures tend to be strongly directional, while the thermal and intermediate energy exposures are much more isotropic (Schuhmacher *et al*, 2006). Neutron fields are also more strongly scattered than photon fields, so the reliance on exposures coming mainly from the front is harder to justify. It is hence very likely that the lower personal dose values seen for lower energy neutrons for irradiations from < 60° (Figure 4.2) will be compensated for by the increased conversion coefficients for higher angles.

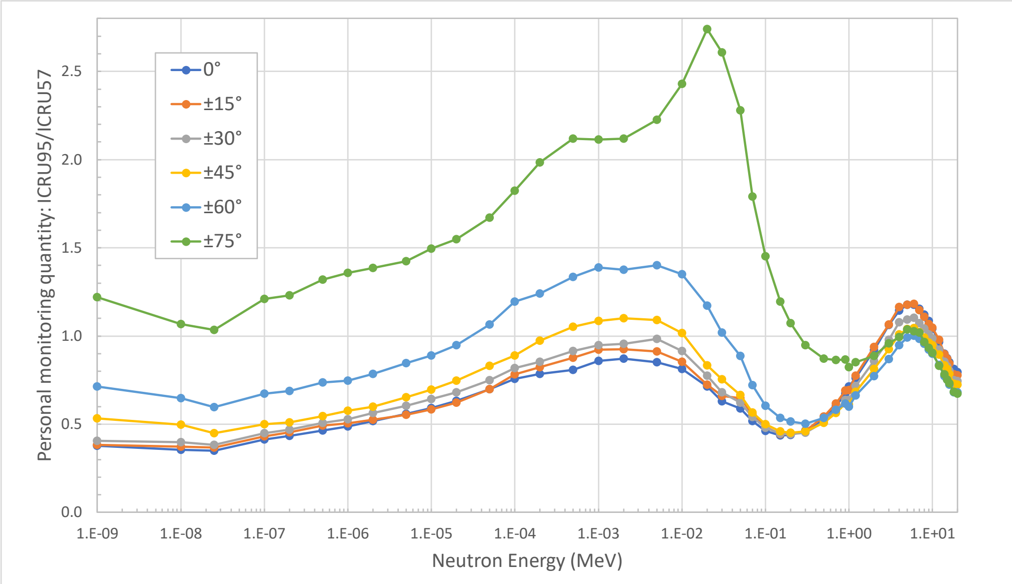

Figure 4.2 Ratio of the H_p to $H_p(10)$ conversion coefficients for angles for which data are available for $H_p(10)$.

Whilst it is not possible to do a full analysis of the difference between personal dose and personal dose equivalent for all angles, because of the lack of available data, it is possible to look at the likely impact in the workplace for the directions for which data are tabulated in ICRU Report 95 (ICRU, 2020). The data (Figure 4.3) show that the significant increases seen for 75° and higher angles incidence are not reflected in overall significance. Even the 90° conversion coefficients when normalized to the 0° data, in the range up to 1 MeV, are only 30% of those for 0° and the maximum value of the ratio, a factor 1.3, is around 200 MeV, decreasing to 1 at higher energies. It should, however, be noted that 90° corresponds to the maximum solid angle, which may be significant for the most strongly scattered component of the field. For energies above 100 MeV the conversion coefficients for irradiation from the front are the lowest of any angle, which could prove significant for accelerator fields, but for cosmic radiation for which ISO or SS-ISO are more relevant direction distributions than any specific angle.

The *personal dose* conversion coefficients for 180° are not negligable for the entire energy range, which they would not be for *personal dose equivalent* if data were available, which will present the same operational difficulty as is seen for photons. The issue is likely to have more impact for neutrons, since they are more strongly scattered than photons and the conversion coefficients for 180° are 50-70% of those for 0° for most of the energy range that covers workplace fields. Like the photon data, it is unfortunate that ICRU have only calculated conversion coefficients for a single “reverse” angle, since the use of a single dosemeter on the front, or dosemeters on the front and back, will need more data to achieve an adequate calibration.

For the eyes and skin there is a big reduction in the operational quantities when compared with those from ICRU Report 57 because the new quantities are based on absorbed dose not dose equivalent, which includes neither a quality factor nor radiation weighting factor in its calculation. The situation is hence very different from that for photons, where for low energies the protection of the eye will be more important than protection of the whole body. For neutrons both eye and skin exposures will be significantly less significant than they are now. However, these statements could become obsolete if the ICRP introduces RBE weighting for neutrons for either tissue, or both. For the eyes this is quite likely because there is no certainty that cataracts are not stochastic for high LET dose deposition. It is hence clear that ICRP needs to resolve this issue before the new operational quantities are implemented. This will have most impact for cosmic ray fields for which neutrons and other high LET radiations contribute a very significant component of the total dose.

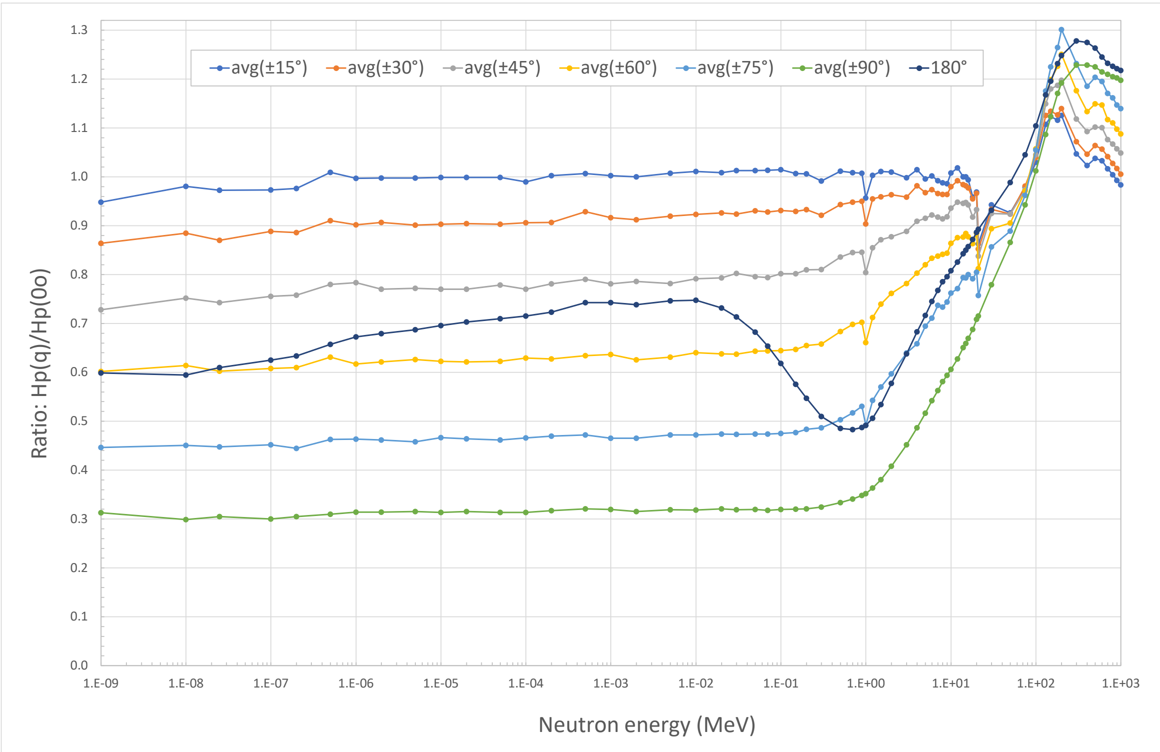

Figure 4.3 Ratio of the H_p conversion coefficient for specific angles (q) to that for incidence from 0°, versus neutron energy.

4.1.3 Cosmic rays

The field in space is characterized by high-energy protons and heavier ions of solar and galactic origin, and their secondary products originated in interactions of those primaries with the spacecraft shielding materials and with the human body. The field in aeronautics is a result of interactions of predominantly solar and galactic protons of high energies with the magnetosphere and the atmosphere of the Earth in which secondary particles are produced, from which the most prominent contributions to radiation expose come from high energy neutrons, protons, pions, electrons, mesons and gamma rays. For both fields it can be said that we deal with energies mostly above 1 MeV. So, from that point of view, one might consider that the new quantities are more adapted for that type of field, because they fall in the high energy domain. But there are other impacts which make the new quantities not very useful for the application or even prevent their use. A detailed description can be found in chapter 4.4 and 4.5.

4.2 RP equipment and facilities

All things being equal in term of irradiation conditions, a change in the assessed doses due to the new quantities, if the dose limits remain unchanged, would have an impact on the shielding design of the facilities. In case of an increase of the operational dose value, shielding would have to be increased and consequently it would eventually lead to better radiation protection. On the other hand, it would have a negative impact in cases where measured operational dose values would decrease significantly. Indeed, consider the example of the exposure of medical staff to low energy X-rays. When using dosemeters designed to correctly measure the new operational quantities, the operational dose values of the staff in e.g. interventional procedures will decrease. In the best case this should lead to a better compliance with the dose limits, and possibly lower operational limits, but in the worst case, this could lead to a worse safety culture for ionising radiation. A wrong perception of lower exposure could lead to a reduction of some protection means, or less effort from the employers and licensees to reduce the doses. Generally, education initiatives and vocational training are mandatory to maintain a proper level of awareness and to implement appropriate radiation protection for the exposed workers.

Ambient monitors that are suitable to measure the operational quantities for photon energies above 70 keV, will still be suited for the new operational quantities. Their design does not have to change. Also the calibration procedures for ambient monitors will not change, but the calibration factors will shift with a certain value. So the whole response of these ambient monitors will shift too. So the monitors where the output can easily be adjusted by the users or the calibration facility, can be used perfectly for the new operational quantities. However, when such adjustment of the display output is not easily done (e.g. when only the manufacturer can do this), these monitors will start giving wrong values. Fortunately the difference is relatively small, a factor of 1.2 for Cs-137 calibration. New calibration factors, as determined by the calibration laboratory will take this change into account. If acceptance criteria are used, more monitors will fail and can no longer be used. For that reason it will be fundamental that calibration factors will be used during measurement and not just kept on paper or files for record management. In some good practices, the calibration factor is indicated on the monitor itself. In either of the two last cases, these new calibration factors which will deviated further from unity, will complicate the on-site measurements, and the risk is that they will not be applied in practice.

4.3 Research activities

The proposed quantities should have an influence on epidemiologic studies. Indeed, for a given cohort of individuals exposed for several years, different ways of considering the dose received will have to be considered. The methods that would have to be implemented to take these differences into account are certainly not trivial.

Moreover, the relationship between dose and effects will change. Even though in theory, this relationship is between the effective dose and the effect, for external radiation from occupationally exposed workers the operational quantities will be used as substitute. The clearest example is the operational quantities values for low energy X-rays, who will decrease. Without care, this could lead to a higher estimated risk per dose unit for such X-ray energies, and consequently, in the long future, to a lower dose limit.

4.4 Radiation fields in space

The concept of operational dose quantities for area monitoring of external exposures, and an assessment of effective dose, are not applicable for space dosimetry, because many different types of particles are involved up to very high energies. Instead the measurement and determination of particle fluence and its distribution in energy and direction are more important, and provide a better basis for an assessment of doses. Although astronauts are exposed to ionizing radiation during their occupational activities, they are not usually classified as being 'occupationally exposed' in the sense of the ICRP system for radiation protection of workers on Earth and for aircraft crew. Instead, astronauts in space are considered to be exceptionally exposed, and the assessment of their individual doses should be part of the radiation protection program used to plan space flight. Thus, for a specific mission, reference levels for risks or doses may be selected at appropriate levels, and no dose limits may be applied for a given mission. As stated by ICRU, the new operational quantities therefore are not applicable of space dosimetry.

The design of spaceflight missions should follow the ALARA principle with the aim of reducing radiation exposures in line with optimization concepts.

Area monitors at well-selected locations in the spacecraft determines the environmental conditions, and are appropriate for an immediate warning about changing of exposure conditions. The assessment of organ and tissue absorbed doses, together with radiation quality factors, of individual astronauts is accomplished by calculations using environmental models that include transport through the spacecraft or spacesuit shielding material into the human body using conversion coefficients (particle fluence to mean absorbed dose in an organ or tissue and mean quality factors) for all particles present. Results are normalized using readings of area monitors and personal dosemeters. Alternatively, absorbed doses are measured at the body of the astronaut then dose equivalents and effective dose equivalent are determined using data from phantom measurements.

For astronauts on the International Space Station (ISS) the calculation of effective dose by the space agencies is performed using the $Q(L)$ - L relationship instead of w_R, as recommended by the Multilateral Radiation Health Working Group (MRHWG) of the Multilateral Medical Operation Panel (MMOP) since the beginning of the operations on the ISS.

NASA calculate risk directly, taking the environmental spectra (from validated models), transport them through the spacecraft shielding into the human body applying the CAM/CAF model (Billings and Yucker, 1973) to calculate organ doses which are normalized using readings of environmental and personal measurements. Same is done by Canadian Space Agency (CSA) and the Japanese space Agency (JAXA), CSA just adapt the NASA procedure, where JAXA uses an own risk approach. The Russian Space Agency (RSA) uses the individual measurements from the astronaut dosimeter as basis of risk estimates applying their own risk model.

The European Space Agency (ESA) calculates a dose equivalent based on the measurements of the European Crew Personal dosimeter. ESA has no own risk model; the ICRP model has been used instead until now.

4.5 Radiation fields at flight altitudes

Aircraft crew are one of the most highly exposed occupational groups. For aircraft activities the radiation weighting factor w_R is used to calculate effective dose. This is done by the use of validated cosmic ray models combined with a Monte Carlo transport model. These calculations showed excellent agreement with the TEPC measurements in the past.

Dose rates are calculated based upon the flight route parameters (longitude, latitude, altitude) and solar activity as well as the time spent in each position. Information on each flight path is supplied by the airlines. The particle environment is calculated using validated cosmic ray models and the simulation of the particle transport, through the atmosphere to the position of the aircraft, using Monte Carlo simulations or by solving the Boltzmann radiation transport in the atmosphere. Several models are in place like AVIDOS (Latocha *et al*, 2009), CARI (US Federal Aviation Administration (FAA, 2014), EPCARD (Mares *et al*, 2009), PCAIRE (Lewis *et al*, 2004), IASON-FREE (Felsberger *et al*, 2009), PANDOCA (Matthiä *et al*, 2014) and SIEVERTPN (Bottollier-Depois *et al*, 2007).

A practical method for validation of codes is by intercomparison campaigns. Yet, the best validation of codes used for assessments of doses to aircrew is a comparison with measurements – it is a common requirement that codes assessing doses to aircrew are able to calculate not only effective dose but also $H^*(10)$, allowing for comparisons with measurements.

4.6 Application of ALARA principle, perception of radiation protection rules

In the ICRU/ICRP report, the use of the sievert unit (Sv) for stochastic effects on the whole body and the gray unit (Gy) for deterministic effects on the eye lens and skin is more consistent than in the current system in which operational quantities are expressed only in sieverts. Changing from sieverts to grays should simplify the understanding of these effects (although whether cataracts are deterministic or stochastic effects is still a matter of debate). It is however difficult to know how this could affect the practices.

The change in quantities can induce a distrust in the radiation protection system. The system of radiation protection quantities is not simple, there are many people, even professionals, who do not know all the detailed aspects of this system. By changing the definition of the quantities, or even the units, the confusion will certainly increase. It will become even more complicated to explain the quantities and the evolution of them to all concerned professionals, let alone to explain this to lay people. The question of the training of professionals therefore arises in a very important way. All this can be compared with the benefit that can be reached by these new quantities.

In addition, part of the world is still using older quantities (like in the USA), and with these new quantities, the risk is that even more divisions will take place all over the world, and that three different quantity definitions will be used alongside each other. Again, this will not help in increasing the trust of the workers and the public in the protection system against the dangers of ionising radiations.

4.7 Conclusions - Impact on RP Practices

The assessment of effective dose is supposed to be more accurate thanks to the new operational quantities. However, this change will lead to changes in the measured dose values for occupationally exposed workers. This will be the case in particular for exposure situations involving low energy x-rays, neutrons and high energy particles. This could lead to changes in approaches to radiation protection in these areas. Care is needed.

n the photon low-energy range, which concerns in particular the medical field and therefore a large number of exposed workers, the new quantities could lead to dose reductions of up to a factor of 6 for specific situations. In most common situations, the dose reduction will be of around factor of 2. This could lead to a decrease in staff vigilance and a reduction in general sensitivity to radiation protection issues.

Big reductions in individual doses are not expected for neutrons, over the whole energy range up to 20 MeV.

For photons as well as for neutrons, the fact of having conversion coefficients for a single "reverse" angle, will complicate the calibrations.

Changes in the assessed operational dose values, if the dose limits remain unchanged, could have also an impact on the shielding design of the facilities. Indeed, a wrong perception of lower exposure could lead to a reduction of some protection means.

The new quantities could also have a practical impact on the use of ambient dosimeters when the adjustment of the dosemeter response is not easy to achieve so that the indicated values do not reflect the operational quantities.

In the research field, the new quantities are expected to have an influence on future epidemiological studies and thus on the established dose-effect relationship. Care is needed in interpretation.

The use of the sievert unit for stochastic effects on the whole body and the gray unit for deterministic effects on the eye lens and skin is more consistent than in the current system, in which operational quantities are expressed only in sievert.

In high-energy and complex fields, such as aeronautics and space, the disappearance of Q(L) from the definitions of the operational quantities will pose practical problems for researchers and experts using microdosimetry techniques whose entire operating principle is based on this quantity. Validation of codes used for assessment of radiation doses to aircrew could still be done using $H^*(10)$; however, this requires that calibration facilities would still offer $H^*(10)$ quantity as reference for appropriate instrument calibration.

Generally, we can ask how the changed doses will affect the application of the ALARA principle. Workers themselves may begin to distrust dosemeters and their results. This should be compared with the benefit that can be reached by these new quantities.

All the changes may induce a certain amount of confusion among involved workers that can be only overcome by a proper professional training.

5. Impact on Calibration and Reference Fields, and International Standards

5.1 General

The impact of the new quantities must be considered for reference fields for calibration and type testing and for the related standards documents. According to ICRU Report 95, section 5.3, calibration procedures will remain largely unmodified. The phantoms for personal dosemeters for calibration and type testing are unchanged from those for the ICRU report 39/51 and described in ISO 4037-3:2019.

5.1.1 The Kerma Approximation and Charged Particle Equilibrium (CPE)

In ICRU Report 95 the following definition can be found: "Charged-particle equilibrium exists at a point if the distribution of charged-particle radiance with respect to particle energy is constant within distances equal to the maximum charged-particle range" and as a consequence, "Under conditions of charged-particle equilibrium, the numerical value of collision kerma at a point of interest equals the value of absorbed dose".

For the current operational quantities, Monte Carlo calculations to determine the dose in ICRU tissue at different depths were performed using the kerma approximation. The kerma approximation assumes that charged-particle equilibrium exists and that the numerical value of kerma is set equal to the absorbed dose in air.

This approach was established decades ago when the capabilities of the available Monte Carlo codes were limited, computational power was limited, and full radiation transport calculations would have been too time consuming. This is justified as, for most workplaces, rather low photon energies prevail (below about 400 keV) and consequently the charged-particle equilibrium condition is already fulfilled by the source housing, the air between the source and the point of interest and material of the detector's entrance window.

In the case of non-CPE, which occurs at higher photon energies, the simplified approach for photons, of using the kerma approximation, results in an overestimation at high photon energies ($E_p > 2$ MeV for $d = 10$ mm, $E_p > 740$ keV for $d = 3$ mm, and $E_p > 65$ keV for $d = 0.07$ mm, (ICRU, 2020, section 2.4)). Likewise for neutrons, CPE cannot be assumed for $E_n > 35$ MeV for $d = 10$ mm, $E_n > 15$ MeV for $d = 3$ mm, because of the range of secondary protons in tissue.

Therefore, to ensure correct and comparable calibration results, ISO 4037 requires for higher photon energies a build-up plate to ensure the charged-particle equilibrium.

The general procedures and definitions for the calibration are defined in the standard ISO 29661:2012 *Reference radiation fields for radiation protection — Definitions and fundamental concepts* and its Amendment 1, valid for all types of radiation. Further procedures for the reference radiation fields relevant for the different particle types are described in ISO 4037 for photons, in ISO 6980 for betas and in ISO 8529 for neutrons. The requirements for type testing are described mainly in IEC standards, see 5.4 Type testing and Table 5.4 below.

5.1.2 New Approach in ICRU 95

(See also 2.8 above.) In ICRU report 95, two sets of conversion coefficients are given for photons. The first set was calculated with full electron transport. Their application requires separate knowledge of the different radiation components such as photons, electrons, and others.

The second set of conversion coefficients for photons, in ICRU 95 Appendix A.5, is valid for charged-particle equilibrium (CPE), calculated with the kerma approximation. These conversion coefficients are used to ensure reliable and comparable calibrations in CPE conditions.

In principle, for calibrations at low and medium photon energies, i.e. below about 400 keV, where CPE is already ensured by the build-up achieved by the air between the radiation source and the dosemeter and other material such as source housings, both sets should result in the same calibration coefficient. In terms of the new operational quantities:

- The “kerma-approximation” set leads directly to the total dose (from all components).
- The “full transport” sets are applied separately to the photon and secondary electron components and the results added to reach the total dose. This requires the spectral and angular knowledge of the photon and the electron component of the radiation field.

5.1.3 Influence of recalibration on type testing

Usually, type test requirements are expressed in terms of the relative response, *r*. The relative response is calculated by dividing the actual response by the response under reference (normalisation) conditions. The reference conditions are either fixed in the corresponding IEC standard (table 5.4) or stated by the manufacturer, especially for the reference dose (rate) and the reference energy. Thus, the relative response under reference conditions is always unity. This approach allows the investigation of the general behaviour of the dosemeter type and cancels out the individual dosemeter calibration. Ideally, the (absolute) response under reference conditions shall be unity.

This approach directly leads to the conclusion, that recalibration of the device alone is often not sufficient to fulfil the type test requirements for the new operational quantities because their energy dependence is different from those of the current operational quantities. The new calibration factor N_{new} will be cancelled out during the calculation of the relative response of the device under test $r(E) = (R(E) \times N_{new})/(R(E_{ref}) \times N_{new})$. Consequently, the result of the type test will not change – unless, at least, another reference energy, E_{ref}, is chosen. In that case, all response, $r(E)$, values will be shifted. Possibly, also a re-design either of the algorithm calculating the dose from the detector signal(s) or even of the dosemeter with its housing, filter materials and their thicknesses will be necessary. See the discussion in chapter 3 above.

The need for a change in the reference energy depends on the energy dependence of the dosemeter under test. The complete energy dependence must be known to choose the corrected new reference energy. No general rule can be applied to calculate the required shift.

5.2 Reference radiation fields

5.2.1 Photon radiations

The reference radiation fields for calibration and testing are defined for photons in ISO 4037:2019, Parts 1-4 (ISO, 2019A, ISO, 2019B, ISO, 2019C, ISO, 2019D). The 2019 revision of ISO 4037 changed its approach to the generation of reference fields. In contrast to the version of 1999 where the requirements were oriented on air-kerma only, all requirements (ISO 4037-1) on the parameters like tube high voltage, filtration etc. are now related to the phantom based quantities, ensuring an uncertainty of about 2 % in the conversion coefficient.

Therefore, after adopting the proposed new quantities, a revision of all requirements to the parameters needed to produce a reference radiation field, like tube high voltage, filtration etc. in the light of the new conversion coefficients is required. It can be expected that in some parameter ranges the requirements will be relaxed and, in some ranges, where the conversion coefficients become steeper, the requirements will be more stringent. Comparing the conversion coefficients of the current and the new quantities reveals that their relative change per energy interval, $\{\Delta h/h\}/\Delta E$, i.e. their relative slope, is smaller for H_p and H^* compared to $H_p(10)$ and $H^*(10)$, respectively, for photons below about 15 keV for both normal and oblique radiation incidence. Near 10 keV the relative slope for the current quantities is about four times as large as the one for the new quantities. Thus, the requirements on the parameters for tube voltages below about 15 kV will become significantly less challenging than they are at present.

For $D_{p\ lens}$ compared to $H_p(3)_{cyl}$ the relative slope is smaller for photons below about 10 keV, especially for oblique radiation incidence. Finally, for $D_{p\ local\ skin}$ compared to $H_p(0.07)_{slab}$ the relative slopes are rather smaller for all photon energies.

The proposed method in ISO 4037 to validate the radiation field by dosimetry with a secondary standard for air-kerma and a secondary standard for the phantom related quantities will not be possible until secondary standards for the new quantities become available. The reason is that the ratio of the current and the new quantities, especially $H_p(10)/H_p$, becomes strongly energy-dependent below about 70 keV. In this energy range it quickly rises to more than a factor of 5 around 15 keV before it strongly decreases again down to zero at about 9 to 10 keV. At 70 keV and above it is nearly independent of energy, i.e., in the range of 1.2 to 1.3. For $H_p(3)_{cyl}/D_{p\ lens}$ and $H_p(0.07)_{slab}/D_{p\ local\ skin}$ such strong differences are only present below about 15 keV and 4 keV, respectively.

The requirements on the new secondary standards have to be defined depending on if they will be used under CPE (calibration fields), as today, or if they will be used under non-CPE (workplace fields), as might be the case in realistic radiation fields, at least in high-energy radiation fields. The latter ones have been one of the main drivers of the development of the proposed new ICRU quantities, as they provide conversion coefficients for photon-only radiation and electron-only radiation up to 50 MeV. Therefore, the contribution of the electrons and the photons must be determined separately, whereas in the current approach (kerma approximation) the electron contribution is defined by assuming the CPE in tissue.

Usually, calibration and testing will be performed in reference radiation fields under full Charged Particle Equilibrium (ICRU report 95, section 5.3.3). This ensures reproducible calibration conditions as non-equivalence conditions would lead to deviating calibration and testing results between different laboratories as the collimation of the source and the electron contamination in the photon beam influence the results.

This should not be the case when the institute determines both photon and electron contributions in their calibration field, folds these energy and angle dependent spectra with the corresponding conversion coefficients for non-CPE, i.e., for photons and electrons, sums up these two dose contributions and uses this as conventional quantity value for the calibration.

The determination of electron spectra is complex. It can be done by simulation of the whole reference field setup and has been performed in the past for the beta reference radiation fields according to ISO 6980. These are freely available as supplementary data files (Behrens, 2013). Further, to simplify the calibration procedure, ICRU decided to allow calibration under CPE, as is the case today: see ICRU Report 95, 5.3.3 Special Provisions for Calibrations With Photons.

From the point of view of ISO, a large influence on the calibration and reference field standards is not foreseen, as calibration and type testing of photon instruments can still be done under CPE in future.

In ISO 4037-2, the dosimetry described is done for the CPE conditions. If it is required to test and calibrate under non-CPE in future, the standard must be updated and new procedures for dosimetry under non-CPE conditions included.

Updated conversion coefficients from air kerma to the new quantities are needed for ISO 4037-3. These values are already available in the literature for CPE conditions for the photon reference radiation fields defined in ISO 4037-1 (Behrens and Otto, 2020) and can easily implemented in an updated version of ISO 4037-3.

The performance of the device under test can be determined for the case of CPE (as is done today) – but the new quantities are designed for non-CPE conditions. Calibration under CPE is just an exemption. But if the device under test *is* able to measure the new quantities, under non-CPE conditions, this is not tested by the CPE-calibration approach. Therefore, it cannot be ensured that the dosemeters will measure correctly in realistic fields, like high-energy photon fields without shielding, where CPE might not be given. Such measurement conditions, without CPE, were one of the drivers for the new quantities; but these conditions are difficult to realise.

If IEC decides to test dosemeters for realistic, non-CPE, conditions then better characterised, new reference fields (ISO) will be needed. The realization of such fields can be done by leaving out the build-up plate but the photon and electron component will have to be determined separately, taking into account the particular irradiation setup (scatter and attenuation on air, source housing/collimator, walls of the irradiation room etc). In turn, this separate determination of photon and electron components will need the development of new instruments that detect the components separately.

In the report, ICRU proposes to use for calibration of personal dosemeters the current phantoms and the new cylinder phantom (ICRU 95, section 5.3.2). The new cylinder phantom is already included in the actual ISO 4037-3:2019 standard, therefore, there is no need for adaptation of the calibration phantoms.

A new standard, ISO/CD 20956 *Low dose rate calibration of instruments for environmental and area monitoring,* is under development to focus on the challenges of calibration at environmental doserate meters. As this standard describes the calibration of environmental monitoring systems, it has to be decided by the corresponding ISO working group on reference radiation fields, i.e. ISO/TC85/SC2/WG2, if the calibration under CPE will be sufficient. As these calibrations are done to check the stable performance of the systems and do not represent a type test, this might be the case.

Pulsed fields are defined in ISO/TS 18090, Part 1 (ISO, 2015F) for photons. For other types of radiation this will be done in the future. No changes are needed for this standard as the pulsation of the field is independent of the measurement quantity.

5.2.2 Beta radiations

The reference beta-particle radiation fields are defined in the ISO 6980 and its parts (ISO 2004, ISO, 2006A, ISO, 2006B) (under revision in 2021).

According to ISO 6980-2 the basic quantity in beta dosimetry is the absorbed dose to tissue in an ICRU 4-element tissue slab phantom at 0.07 mm depth, $D_t(0.07)$. This is usually measured using an extrapolation chamber mounted in a slab phantom (often made of PMMA). Conversion coefficients from $D_t(0.07)$ to the current operational quantities are available in ISO 6980-3:2006 for $H_p(0.07)_{slab}$ (based on measurements in a slab phantom) and are assumed to be equal for $H'(0.07)$, i.e. for the same depth in the ICRU sphere. Recently, correction factors have become available to account for the differences between the slab and the sphere as well as the rod (Behrens, 2015). Furthermore, measured values for 3 mm depth are available to arrive at $H_p(3)_{slab}$ (Behrens and Buchholz, 2011); while correction factors to account for the differences between the slab and the cylinder to arrive at $H_p(3)_{cyl}$ are also available (Behrens, 2015). All these data are currently implemented in ISO 6980 within its ongoing revision for the current operational quantities. For the new quantities, these correction factors were updated (Behrens, 2021) and can easily be implemented in a further revision of ISO 6980-3.

5.2.3 Neutron radiations

Reference neutron radiation fields are defined in ISO Standard 8529 which has the generic title *Reference neutron radiations,* and consists of three parts:

- Part 1, ISO 8529-1:2021 *Characteristics and methods of production;*
- Part 2, ISO 8529-2 2000 *Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field*, and
- Part 3, ISO 8529-3 1998 *Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence.*

These standards are under revision. The revision of Part 1 was finished in 2021, and work has started on Parts 2 and 3, however the conversion coefficients that will be referenced, for both monoenergetic fields and broad ranged radionuclide fields will be for ambient and personal dose equivalent. Updating to the new operational quantities will be a task for a subsequent revision.

The basic quantity in neutron metrology is the neutron fluence (neutrons cm^{-2}) or the fluence rate (neutrons cm^{-2} s^{-1}). The operational quantities and their rates are derived from these basic quantities simply by multiplying by the conversion coefficient from fluence to the relevant operational quantity. Transition to the new ICRU quantities should thus present no problems for calibration labs following ISO 8529. Neutrons for the majority of the fields recommended in the standard are produced in a small volume/area which can normally be approximated as a point for commonly used source to detector distances, ≥ 75 cm, so the directional properties of the fields are those of a point source. The exceptions are thermal fields and reactor filtered beams. The latter, as the name suggests, are a beam and hence the field has well defined angular properties. Thermal fields are usually either a beam or an isotropic field so both have angular characteristics for which there are fluence to dose conversion coefficients for the new quantities.

For monoenergetic fields conversion coefficients can be taken directly from the tables in ICRU 95 although interpolation may be necessary. In principle, with unidirectional fields, calibrations can be performed at any angle of incidence on the dosemeter, although 90° presents problems for a slab phantom. The lack of conversion coefficients between 90° and 180° mean these angles cannot be covered. However, the degree to which a calibration at these angles would be meaningful with a slab phantom is questionable.

For fields produced by radionuclide sources spectrum averaged conversion coefficients are required. These are shown in Tables 5.1 to 5.3 where they are compared with those for the original operational quantities. The numbers in these tables have not yet been confirmed by incorporation in standards documents, but give a clear indication of the changes to be expected for the new quantities.

Table 5.1: Spectrum-averaged conversion coefficients for a ^{252}Cf source derived using spectral data from ISO Standard 8529-1. Values for $h^*(10)$ and $h_p(10,\alpha)$ are from part 3 of the standard (ISO 8529-3), and are compared with values calculated with the new ICRU 95 coefficients. Units are pSv cm^2.

	Ambient	Personal					
Angle α		0°	15°	30°	45°	60°	75°
$h^*(10)$ or $h_p(10)$ from ISO 8529-3	385	400	397	409	389	346	230
h^* or h_p using ICRU 95 coeffs	352	352	353	337	309	267	213
ICRU 95 / ISO 8529-23	0.914	0.880	0.890	0.824	0.794	0.772	0.925
Angle		90°	180°	ROT	ISO	SS-ISO	IS-ISO
h^* or h_p using ICRU 95 coeffs		150	210	224	180	188	172

Table 5.2: Spectrum averaged conversion coefficients for an ^{241}Am-Be source derived using spectral data from ISO Standard 8529-1. Values for $h^*(10)$ and $h_p(10,\alpha)$ are from part 3 of the standard (ISO 8529-3), and are compared with values calculated with the new ICRU 95 coefficients. Units are pSv cm^2.

	Ambient	Personal					
Angle α		0°	15°	30°	45°	60°	75°
$h^*(10)$ or $h_p(10)$ from ISO 8529-3	391	411	409	424	415	389	293
h^* or h_p using ICRU 95 coeffs	427	427	427	412	385	342	285
ICRU 95 / ISO 8529-23	1.092	1.039	1.045	0.972	0.928	0.880	0.974
Angle		90°	180°	ROT	ISO	SS-ISO	IS-ISO
h^* or h_p using ICRU 95 coeffs		210.9	292.6	295.6	242.9	253.2	232.7

Table 5.3: Spectrum averaged conversion coefficients for the D_2O moderated ^{252}Cf source derived using spectral data from ISO Standard 8529-1. Values for $h^*(10)$ and $h_p(10,\alpha)$ are from part 3 of the standard (ISO 8529-3), and are compared with values calculated with the new ICRU 95 coefficients. Units are pSv cm^2.

	Ambient	Personal					
Angle α		0°	15°	30°	45°	60°	75°
$h^*(10)$ or $h_p(10)$ from ISO 8529-3	105	110	109	109	102	87.4	56.1
h^* or h_p using ICRU 95 coeffs	91.4	91.4	91.7	87.3	79.6	68.6	54.5
ICRU 95 / ISO 8529-23	0.870	0.831	0.841	0.801	0.780	0.785	0.971
Angle		90º	180º	ROT	ISO	SS-ISO	IS-ISO
h^*or h_p using ICRU 95 coeffs		38.4	56.3	58.2	46.7	48.8	44.6

For both bare and heavy water moderated ^{252}Cf the conversion coefficients for the new quantities are smaller than for the current quantities, significantly so for the heavy water moderated spectrum. For ^{241}Am-Be neutrons the coefficients are slightly larger for angles between 0° and 15° but are smaller at larger angles.

For secondary calibration labs the requirement for traceability to a recognised national standard is achieved by using a transfer standard to provide the calibration link. The actual device will depend on the type of field and could be, for example, a well-characterised radionuclide source or an appropriate transfer instrument. As the quantity validated is the fluence, the introduction of the new quantities should not change matters provided the measures outlined in ISO 8529-2 to ensure and demonstrate valid traceability are followed.

For simulated workplace neutron fields, the following standard is valid. ISO 12789 Reference radiation fields — Simulated workplace neutron fields with Part 1: Characteristics and methods of production and Part 2: Calibration fundamentals related to the basic quantities, (ISO, 2008B, ISO, 2008C).

Except perhaps for the D_2O moderated ^{252}Cf source, there is no standard design for a simulated workplace field. All the examples given in ISO 12789-1 are different, available only in one place, and several of them are no longer operational. Any facility offering a simulated workplace field must therefore calculate the operational quantity, and this requires information on both the spectrum and the directional properties of the field. Conversion coefficients are available as functions of both energy and angle, but deriving all the required spectral and directional information may be difficult in particular as the directional properties may depend on the energy region in the spectrum. An example of this would be a field consisting of a direct component from a source, which would be unidirectional and most probably high energy, with the addition of a scattered component from the room, which would be lower energy and possibly isotropic.

5.2.4 Protons, Neutrons and Heavy ions

For the calibration of the instruments used in aeronautics and space high-energy Proton/Ion accelerators are used. However, at flight altitudes, usually the quantity effective dose is used for the monitoring of persons. In cases where $H^*(10)$ is used to estimate the effective dose, it would have to be changed to H^*.

Reference fields needed for photon, electrons and neutrons are the same as used for other activities.

5.3 Intercomparisons, key and supplementary

The rules for key comparisons for National Metrology Institutes (NMI) are given in the EURAMET Guide No.4 for Key Comparisons and Supplementary comparisons. Intercomparisons of, e.g., Individual Monitoring Services (IMS) are carried out according ISO 14146:2018 "Radiological protection — Criteria and performance limits for the periodic evaluation of dosimetry services".

The procedure for intercomparisons for calibration laboratories will remain unchanged. The measurements will be done under full CPE as today. As the slope of the conversion coefficients has changed, new secondary standards and transfer instruments are needed urgently.

For intercomparisons of laboratories offering testing under non-CPE, additional requirements and procedures will have to be developed and validated.

ISO 14146 (ISO, 2018) will need to be updated to adopt the new quantities, which will be straightforward for CPE conditions. For non-CPE conditions corresponding procedures will need to be added referring to the relevant parts of the correspondingly updated ISO 4037 (ISO, 2019A, ISO, 2019B, ISO, 2019C).

5.4 Type testing

IEC (type test standards) will wait till the new quantities are adopted by IAEA and EC which may take several years. Then, if they are adopted, a meeting between the dosimetry experts of ISO, IEC and EURADOS could take place in order to define a strategy how to proceed.

The many standards containing performance requirements for dosemeters are listed in table 5.4. To account for the new quantities all these standards need to be slightly updated referencing the correspondingly updated ISO standards on reference radiation fields. Photon type testing will inevitably need to make use of the kerma-approximation conversion coefficients. In standards for photon dosemeters also non-CPE conditions are needed to determine the instrument performance in realistic radiation fields – see chapter 3.2.

The revised standards will need to take into account the performance, in terms of the new quantities, achievable by instruments and dosemeters. It may be that performance limits need to be looser, for example for the photon and beta energy dependences of response for extremity dosemeters.

Table 5.4: Standards applicable to devices

Type of radiation	area dosemeters		personal dosemeters	
	active	passive	active	passive
Photon	IEC 61017, 2016 (environmental) IEC 60532, 2010 (fixed installed) IEC 60846-1, 2009 (portable) IEC 60846-2, 2015 (emergency)	IEC 62387, 2020 (all passive dosemeters)	IEC 61526, 2010 (in revision, CDV in 2021-12) (all active dosemeters)	IEC 62387, 2020
Beta	IEC 60846-1, 2009	IEC 62387, 2020	IEC 61526, 2010	IEC 62387, 2020
Neutron	IEC 61005, 2014 IEC 61322, 2020 (fixed installed)	---	IEC 61526, 2010	ISO 21909-1, 2021 (all passive) ISO 21909-2, 2021 (energy dependent)

Source:
www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm_lst.pdf

Title, status and year of publication of the standards in Table 5.4:

IEC 60846-1	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; 2009-04 EN 680846-1:2014
IEC 60846-2	Radiation protection instrumentation - 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; 2015-12; EN 680846-2:2018
IEC 60532	Radiation protection instrumentation - Installed dose ratemeters, warning assemblies and monitors - X and gamma radiation of energy between 50 keV and 7 MeV; 2010-08
IEC 61005	Radiation protection instrumentation - Neutron ambient dose equivalent (rate) meters; 2014-07; EN 61005:2004; DIN EN 61005:2005 (VDE 0492-2-2)
IEC 61017	Radiation protection instrumentation – Transportable, mobile or installed equipment to measure photon radiation for environmental monitoring; 2016-02
IEC 61322	Radiation protection instrumentation - Installed dose equivalent rate meters, warning assemblies and monitors for neutron radiation of energy from thermal to 15 MeV; 2020-01
IEC 62387	Radiation protection instrumentation - Passive integrating dosimetry systems for environmental and personal monitoring of photon and beta radiation; 2020-01; EN 62387:2020 (IEC 62387:2020, modified)
IEC 61526	Radiation protection instrumentation –Measurement of personal dose equivalents $H_p(10)$ and $H_p(0,07)$ for X, gamma, neutron and beta radiations – Direct reading personal dose equivalent meters and monitors; 2010-07; *under revision*; EN 61526:2013 (IEC 61526:2010, modified)
ISO 21909-1	Passive neutron dosimetry systems - Part 1: Performance and test requirements for personal dosimetry; 2015-11; *under revision*
ISO 21909-2	Passive neutron dosimetry systems - Part 2: Methodology and criteria for the qualification of personal dosimetry systems in workplaces; FDIS (2021)

5.5 Chapter summary and conclusions

For photons, betas and neutrons, the values of the new conversion coefficients have to be adopted. The radiation fields themselves can remain as they are, provided that calibration and type testing is done for photons under CPE only. For non-CPE conditions, reference radiation fields and dosimetry protocols (ISO 4037-2) are needed.

- In contrast to ICRU Reports 39/51/57, the ICRU Report 95 states modified conversion coefficients for photons, electrons, neutrons and new for protons, muons, pions and helium ions.
- Several ISO, IEC and IAEA standards have to be extensively revised. This will take some years if people are willing to do the work. It is costly and time consuming. In some cases, there might not be enough interest to do this within a reasonable time. In the short to medium term, a loss in harmonization of instruments could be the result.
- For photons, normal calibration and testing, including type-testing, will be done in reference radiation fields under Charged Particle Equilibrium (CPE). If the device under test is able to measure under non-CPE this will need to be tested separately and the conditions prevailing during the test. In particular, the contributions to the dose expressed by different particle types (e.g., photon and beta) and energy and angle distributions (spectrum), will need to be described in the test report or calibration certificate.
- To ensure the benefits of the proposed quantities, the independent measurement of the different radiation components, especially the electrons, is required. If this approach is taken, new instrument designs will be needed. Since the detectors for electrons are mechanically very sensitive, the application in high-energy fields as they occur at accelerator facilities and nuclear power plants becomes difficult. Here, the working conditions require robust instruments.
- Converting the indication of current quantity values to the proposed new ones is almost impossible as knowledge of the specific exposure situation, i.e., energy and proportions of the various radiation components, is essential. Using a simple conversion via factors makes the application of the new concept pointless, as their advantage would be lost. In particular, the assumption of CPE at higher photon energies and the drastically changed slope at lower photon energies conflicts with the basic concept of the proposed new quantities.
- The secondary standards developed for the current valid phantom-based quantities are not appropriate for the future quantities. Particularly in case of using secondary standard instruments for measurements in realistic radiation fields under non-CPE conditions, a complete redesign of the standard instrument is needed, because the different radiation contributions need to be determined. In the case of the actual phantom-based quantities, this is solved by assuming or creating CPE for photon measurements. This was one main issue for proposing new quantities besides large energies (above several MeV) and ions. As one of the benefits of the proposed new quantities applies only in case of non-CPE, instrumentation must be able to measure the different radiation contributions in terms of energy distribution and dose and summing them up to the dose. Especially in the range of lower photon energies of up to 100 keV, due to the path length of the electrons, it can be assumed that CPE is present under all conditions. But even for this energy range, due to the adoption of the new quantities, a change of nearly a factor of 5 has to be faced. Therefore, current secondary standards do not fulfil the requirements defined in ISO 4037-2 (see above). Consequently, there is an urgent need for the development of novel secondary standards

and transfer instruments for use in non-CPE applications. As the market is small, there is a strong need for research funding.

6. Impact on Regulation (including Dose Registries etc.)

6.1 Potential Changes in the European Basic Safety Standards

The Basic Safety Standards (BSS) for protection against the dangers arising from exposure to ionising radiation is the main legislation document, issued as a European Directive. The latest BSS, known as Council Directive 2013/59/EURATOM, was published on December 5, 2013 (Council for the European Communities, 2014) and repealed former directives, the most recent being directive 96/29/EURATOM (Council for the European Communities, 1996). The Directive was prepared by a task group from the Group of Experts of Art.31 EURATOM treaty. The BSS define basic standards for the protection of the health of workers and the general public against the dangers arising from ionising radiations.

Introducing the new operational quantities will require surprisingly little, and rather noncontroversial, modifications of the Directive:

i) The current Directive refers to several reports issued by the International Commission on Radiological Protection, ICRP, mainly No. 103, 116 and 119. Point (10) of the preamble states that: *"For external exposure, values and relationships have been published following the new methodology in ICRP Publication 116. These data, as well as the well-established operational quantities, should be used for the purpose of this Directive."* It is also pointed out at point (14) that the current Directive follows the new ICRP guidance on the limit for equivalent dose for the lens of the eye in occupational exposure. As noted above, the standard refers to "…well-established operational quantities which should be used for the purpose of this Directive". Any future Directive should then additionally take into account the ICRU/ICRP report 95.

ii) Article 13, 'Estimation of the effective and equivalent dose', which currently refers to the operational quantities described in ICRP 116 (ICRP, 2010), should instead be related to ICRU 95 (ICRU, 2020).

The BSS are transposed in national legislations, so the same changes will also be needed there.

6.2 Legislation timeline

There is a major concern of dosimetric services regarding how to cover the costs of modifying personal dosimeters so that they are able to properly determine the new operational quantities. The possible legislation timeline is therefore of great interest for such services, and for the wider industry.

The publication of the previous BSS (96/ 29/EURATOM) took place in 1996, i.e. 17 years before publishing the current version in 2013. Once published, all member states had 4 years to adapt their national regulations to meet the Directive. The preparation of the recent BSS by the task group of Article 31 of the EURATOM Treaty and the legislation process took approximately 4 years. If the dynamic of this process is comparable to what it has been in the past, work on the next BSS is likely to start around 2026, publication would then be expected around 2030, and it would not be introduced to national regulations until 2034. This gives approximately 12 years for the industry to find and test technical solutions for the new dosimeters. Publication of ICRU/ICRP Report 95 is expected to initiate a number of publications and analyses, as happened after the previous publications of Directives.

6.3 Supporting documents

In addition to the legislation there are many other documents that will need to be updated.

The BSS are further explained and elaborated into practical documents by the IAEA, in a series of safety guides. There are more than 20 of these general safety guides. Many of them refer to, or use, dosimetry aspects, and will thus require an update. The most important one for the operational quantities is 'GSG7: Occupational Radiation Protection'. This report was published in 2018, i.e. about five years after the new BSS were published. A similar delay can be expected after the next BSS is updated with the new operational quantities.

There is also a series of specific safety guides, focussed mainly on nuclear power plants, but some also give guidance on radiation protection for other specific activities, like industrial radiography. Again, all documents that refer to the operational quantities will need updating.

The IAEA also has a series of TECDOCs, of which there are nearly 2 000 such publications. These TECDOCs will not be updated, although the new quantities will make some of them obsolete. New TECDOCs will have to be made with the new quantities in mind.

ISO and IEC documents will also need a thorough update, as described in chapter 5. But there are also other documents that can be considered important for supporting or organising occupational radiation protection and, more specifically, dosimetry. It is not possible to list here all relevant documents that will need an update. Such a list would include scientific books, university guidebooks, national guidelines, guidelines from WHO, ILO and EC, documents from associations such as IRPA and NEA, guidance documents from organisations such as EFOMP and EURADOS, and others.

One of the most important documents is RP 160: 'Technical Recommendations for Monitoring Individuals Occupationally Exposed to External Radiation'. This document provides guidance for dosimetric services, and was initiated by the EC and published in 2009. A new version of this document should be prepared in the next few years, taking into account the new operational quantities.

There are, of course, also a lot of teaching documents and courses that will need to be updated. Furthermore, the teachers of those courses will need first to be trained to understand the new quantities.

6.4 Dose registries

Dose record keeping is the making and maintaining of personal dose records for radiation workers. It is an essential part of the process of monitoring the exposure of individuals. Apart from demonstrating (the degree of) compliance with legal regulations (dose limits), record keeping may also be used for several additional needs and applications, such as:

- to demonstrate the effectiveness of ALARA;
- to provide data for analyses of dose distributions;
- to evaluate trends in exposure (possibly as a function of work practices or radiation sources), which is necessary for evaluation of a radiation protection system;
- to develop effective monitoring procedures and programmes;
- to provide data for medical and/or legal purposes;
- to provide data for epidemiological and research studies.

All countries should create and maintain a national dose register, where the dose values received by workers monitored in the country are kept for time intervals longer than their working life and the life-time of the employer. In some countries, an Approved Dosimetry Service (ADS; not necessarily the same ADS that assesses the doses) may maintain the dose records on behalf of the employer (undertaking).

In addition to this, the BSS stipulates that employers, registrants and licensees shall maintain records of occupational exposures for every worker for whom assessment is required, and gives general provisions on the content of those records in the national dose register. In particular, it is required in the BSS that "*The results of the individual monitoring of the exposed worker shall include the official dose record (year; effective dose in mSv; in the event of non-uniform exposure, equivalent doses in the different parts of the body in mSv; and in the event of an intake of radionuclides, the committed effective dose in mSv)*".

Whilst the various databases store the values of the protection quantities, for external dose measurements it is the operational quantities that are used to estimate those values. It should be made clear in the databases exactly which operational quantities were used and when the change took place. This is particularly important when data from a dose database will be used for epidemiological studies, because the inferred value of effective dose will depend on the operational quantity used to estimate it. This raises the possibility of revising old effective dose values to obtain a consistent set of values for these studies.

6.5 Impact on dose limits

Publication of the ICRU/ICRP Report 95 may initiate discussion if, following the new operational quantities, the dose limits (or some dose limits) also need to be changed.

For some radiation qualities, the dose values that are actually measured will change significantly. The clearest examples are the operational quantities for low energy X-rays, the doses from which will decrease. In theory, this could lead to a higher estimated risk per dose for such X-ray energies, and consequently (in the longer term) to a lower dose limit. This will have an impact on future epidemiological studies: the relationship between dose and effects will change. Even though, in theory, this relationship is between the effective dose and the effect, for external radiation from occupationally exposed workers the operational quantities are mostly used as substitutes.

In fact, the situation can become quite difficult for epidemiological studies using the operational quantities. They will end up with results coming from a mixture of quantities, and it will not be easy to convert from one quantity to another because the result will depend on the energy and angle of the radiation, which are mostly not well known. Such problems also occurred in the past when the quantity definitions changed previously, but this time the changes are more substantial for some types and energy of radiation.

It is recommended that radiation protection measures are not relaxed as a result of the change to the new operational quantities.

6.6 Aircrew and Astronaut Dosimetry

For exposure to cosmic radiation in aircraft altitudes, the standard ISO 20785 "Dosimetry for exposures to cosmic radiation in civilian aircraft" is applicable with is parts:

- Part 1: Conceptual basis for measurements (ISO, 2020A)
- Part 2: Characterization of instrument response (ISO, 202B)
- Part 3: Measurements at aviation altitudes (ISO, 2015C) and
- Part 4: Validation of codes (ISO, 2019E).

Introducing the new operational quantities calls for an update for at least parts 2 and 4.
In ICRU report 84 (ICRU, 2010), reference values in terms of $H^*(10)$ were published for validation of doses from cosmic radiation exposure of aircraft crew. If the new operational quantity, H^*, is to be used instead, then new sets of reference values will be needed.

For aeronautics the TEPC is used as reference instrument. It delivers the information needed to estimate aircrew radiation risk. Of course, it cannot directly measure H^*, as required by this new ICRU quantity. But – properly calibrated – it should be kept as a reference instrument because it provides the best available estimate of effective dose for air crew. For strict quality assurance, this implies that calibration facilities continue to offer $H^*(10)$ as a reference quantity.

For space dosimetry, no impact is foreseen by ICRU. Operational quantities based on the radiation weighting factors defined by ICRP are considered not justified by ICRP123 recommendations and would overestimate the contribution of the heavy ion component of cosmic radiation considerably.

7. Conclusions

7.1 Main Conclusions

7.1.1: Redesign of Dosemeters and Instruments

Many types of passive dosemeters and some instruments will need a measure of redesign, and in some cases – typically single-element dosemeters – this redesign will be radical and costly.

- For some types of device it will be possible to simply change the calibration, e.g. the calibration factor of an instrument or the effective calibration energy for a dosemeter.
- For other types, it may be possible to retro-fit modifications, e.g. adding different filtration, to obtain an acceptable response. Costs will be involved here.
- The existing over-response of some dosemeter types – including those using "conventional" lithium fluoride LiF (Mg, Ti) – will, in the lower photon energy range, be made worse.
- For multi-filter dosemeters it should be possible to apply or adapt algorithms to achieve an acceptable H_p response, but more work is needed to confirm this. Probable measurement uncertainties also need to be evaluated.
- Otherwise, a redesign of dosemeters will be necessary in order to regain satisfactorily flat response characteristics across the required energy and angle ranges. That process will be costly, and in some cases prohibitively so.
- Extremity dosemeters will only be able to provide good estimates of the new quantities if the kerma-approximation conversion coefficients are used (see 7.1.3 below).
- Given that some of the necessary changes will be radical, and that there is a limit to how gradually new designs can be implemented, it is not the case that the changes are "reasonably straightforward" (ICRU, 2020, section 1.1).

7.1.2 Reduced Doses in Diagnostic / Interventional Procedures

Introduction of the new operational quantities will see an apparent reduction in collective whole body doses arising from diagnostic/interventional procedures.

i) The reduction is ONLY apparent – the actual doses, as represented by the protection quantities, will not change.
ii) This should not lead to any easing of radiation protection measures.
iii) By contrast, eye lens doses will not change. It will therefore become much more difficult to control eye lens doses by controlling whole body doses.

- When the new operational quantities are adopted, there will be a significant decrease (a factor of 2 or more) in measured whole body doses arising from diagnostic/ interventional procedures, not only in the medical sector but also in veterinary and dental practice. The reduced doses arise because the H_p conversion coefficients are lower than those for $H_p(10)$ in the energy range used in X-ray diagnostic and interventional procedures. The reduction is to be welcomed, because the new operational quantities give a better estimate of the protection quantities than the old ones do over this range. However, care will be needed when interpreting these lower doses.
- In particular, it must be understood that the "true" doses – as represented by the protection quantities – received by individuals are not in fact changing. (The new operational quantities will, in this energy range, give a better estimate of the protection quantities; but in previous optimisation exercises, differences between the operational and protection quantities ought

to have been taken into account.) There is therefore no justification for radiation protection measures to be relaxed.

- Eye lens dose will not change significantly. $D_{\text{eye lens}}$ conversion coefficients are, except at high photon energies, similar to those for $H_p(3)$. This means that any current practices in which eye lens dose is controlled by means of whole body monitoring are unlikely to work.

7.1.3 Calibration and Type Testing: the Kerma-Approximation Conversion Coefficients will be Widely Used

For conversion from K_a to the operational quantities, the ICRU report contains both "full transport" conversion coefficients (CCs) and "kerma approximation" CCs. In practice, it will be the kerma-approximation CCs that are mostly used.

- According to ICRU 95, section 5.3, calibration procedures will remain largely unmodified with the introduction of the new quantities. The phantoms for personal dosemeters for calibration and type testing are unchanged. International standards on calibration and testing will have to be revised to accommodate the new quantities, although this could amount to little more than changing conversion coefficients.
- For **photons**, attention needs to be paid to the question of charged particle equilibrium (CPE). The coefficients for kerma to operational quantities currently in use were calculated using the 'kerma approximation', i.e. for CPE. In ICRU 95, conversion coefficients are presented both for non-CPE and CPE conditions. The former set of conversion coefficients was calculated with full electron transport, and their application needs separate knowledge of the different radiation components such as photons, electrons, and others; it also needs physical laboratory conditions which cannot be fulfilled.
  - For this reason, it is the "kerma approximation", CPE-based data that will normally be used by calibration and testing labs when the new quantities come into use and the approach defined in the ISO 4037 series of standards will continue to be used, with all the currently employed additional refinements (build-up plates) in place to ensure CPE at the detector.
- For **beta** radiation, the approach to calibration is covered in the standards of the ISO 6980 series which is currently undergoing revision (not in order to introduce the new quantities but rather $H_p(3)$, and other topics). The complication with beta reference radiations is that they are not mono-directional and cannot be easily measured, so the coefficients from ICRU 95 cannot be used directly. A complete set of coefficients for the new quantities for use with calibration sources has, however, already been calculated (Behrens, 2021) and are available for inclusion in the next revision of ISO 6980.
- For **neutrons**, the only modification required is to implement new fluence to dose quantity conversion coefficients. For monoenergetic neutrons the conversion coefficients can, after interpolation if necessary, be taken directly from ICRU 95, while coefficients for commonly used radionuclide sources are presented in this report.
- As the application of new conversion coefficients for photons (the kerma-approximation versions), betas and neutrons is the only significant change, results from calibrations already performed can be converted to those for the new quantities, by using the new conversion coefficients if the fluence or kerma was given in the original certificate, or simply by multiplying any existing calibration factor with the ratio of the new to the old conversion coefficients. Although new calibrations will eventually need to be performed this approach

should at least give an indication of the extent to which device responses will change on introducing the new quantities.

7.1.4 Limited Impact in Space and Aircrew Dosimetry

For aircrew dosimetry, the new operational quantities are of limited use. Dose calculations go directly to effective dose (aircrew). ICRP does not recommend specific operational quantities for space dosimetry, but considers the application of radiation weighting factor based quantities as not justified.

- For aircrew dosimetry, the new operational quantities are of limited use. The widely-used dose calculation programs go directly to effective dose. Currently $H^*(10)$ is used for code validation measurements. One might expect that H^* would, under the new scheme, fulfil the same function. However, H^* cannot be measured with the TEPC, as $H^*(10)$ can (see 6.6 above). First model estimates indicate that a correction factor to the TEPC measurements could be used to estimate H^* (Matthiä *et al*, 2022). Therefore, either the TEPC should continue to be used, or sophisticated instruments, measuring the dose contribution of the different radiation components separately, will need be developed.
- For space dosimetry, ICRP does not propose the use of operational quantities. Recommended instead is the calculation of effective dose equivalent using conversion coefficients of particle fluence to mean absorbed doses in organs or tissues, and mean quality factors for protons, neutrons, charged pions, alpha particles and heavy ions ($2<Z\leq 28$) for females and males using the reference Voxel phantom (ICRP, 2009). Although the new operational quantities (ICRU, 2020) do allow for dose calculation up to higher radiation energies, this does not change ICRP's position.

7.2 Benefits

The new quantities should bring with them benefits that will result in better radiological protection, in terms of better estimation of worker doses. The benefits will arise chiefly for radiations in the diagnostic/interventional photon energy range, and for higher-energy radiations such as those generated in particle accelerators.

Areas where benefits will arise

- The new quantities provide a better estimate of risk than the current, ICRU 47 (ICRU, 1992), quantities. This was one of the primary intentions behind the new quantities, which are designed to be closer surrogates for the protection quantities and therefore better estimators of risk.
- Switching to D for tissue reactions does bring some advantages, e.g. in differentiating between tissue reactions and the stochastic effects associated with H_p. However, ICRP are still considering whether it is correct to treat eye lens cataract formation as a tissue reaction. It is therefore too soon to fully endorse the switch.
- For medical diagnostic / interventional applications using x-rays, the use of the new operational quantities will reduce the current overestimation of effective dose. Education is needed to ensure that stakeholders appreciate that although the measured doses will fall, the effective doses – which most closely represent detriment – will stay the same. When this is understood, changes to practice and premises can properly be considered.
- As mentioned above, in space and aircrew dosimetry the impact of the new operational quantities will be minimal. However, in other high-energy fields such as those around

particle accelerators and proton therapy units, the new quantities should allow consistent assessment of worker doses and more efficient use of radiological protection resources.

7.3 Costs and Resource Impacts

In adopting the new operational quantities there will inevitably be significant costs, both in resource terms and financial terms. These will arise from the need to:

i) type test all dosemeters and instruments, whether redesigned or not, in terms of the new quantities.
ii) redesign instruments and dosemeters.
iii) re-issue a wide range of international standards, including those for type-testing.

In order to fully implement the new operational quantities, additional resources will need to be allocated. These will each generate costs. As pointed out in ICRU 95 (ICRU, 2020), some of these costs can be spread over a period of ten years or more. Others will have to be met over a much shorter period, e.g. when rolling out a redesigned instrument or personal dosemeter.

Further, it is likely that different countries will adopt the new quantities at different rates. This is not surprising; it echoes the history of the existing operational quantities. However, in the present case, concerns about costs could particularly affect countries whose radiation protection resources are limited. These considerations mean that full adoption might not be achieved until the late 2030s. During such a lengthy transition period there would necessarily be a loss of harmonisation, with different countries using different quantities.

The main areas where costs will arise are:

- Re-design of instruments, personal dosemeters and algorithms.
- Modified instruments and personal dosemeters:
    - development
    - production
    - roll-out (and withdrawal of obsolete versions).
- Revision and re-issue of international standards:
    - calibration (field production, procedures, conversion coefficients for fields)
    - type testing (taking into account the ability of existing and new dosemeters to measure the new quantities)
    - practice (e.g. proficiency testing, recommendations on procedures, measurement uncertainties).
- Training and information for:
    - radiation protection experts.
    - legislators/ competent authorities.
    - health and safety supervisory staff.
    - individual monitoring service staff.
    - workers.

To fully support the training and information processes, a planned communication programme will be needed, both internationally and nationally.

Such costs, indeed, arose when the old ICRU (reports 39, 43 and 47) operational quantities were introduced, arising from all the needs mentioned above. Amongst the benefits were that the quantities were for the first time additive, and this led to a welcome standardisation and a firm basis from which to design instruments, dosemeters and calibration systems.

But in adopting the new quantities, the costs will now be higher because the existing systems are very firmly established, while the number of standards that will need review has increased. It is not clear at this stage that the benefits arising from adopting the new quantities will outweigh the costs. Further work on this topic is recommended.

Because the consequences are wide ranging and because the development of new equipment and processes will take time, it is further recommended that funds are made available, at both national and international levels, as soon as possible.

7.4 Future Changes

The new operational quantities are defined for the present definition of effective dose, and for the current phantoms, as described in detail in the ICRU report. This means that the conversion coefficients are fixed also for the future, regardless of any changes in the phantoms or protection quantity definitions. ICRU has explained that they expect any future changes in the definition of E or the phantoms used to calculate E would lead to only minor deviations from the present (and final) conversion coefficients. In other words, any future change will mean that the present operational quantities will no longer be perfectly matching with the protection quantities, but these differences are assumed to be negligible.

Of course, these are just assumptions. From past experiences it can be believed that changing to new phantoms (like BREP or NURBS phantoms) would not make a major difference. But it cannot be predicted how much the radiation or tissue weighting factors will change with new scientific evidence. There have been substantial changes in the past.

7.5 General Recommendations

This report is just part of the process of evaluating the impact of the new operational quantities. There is considerable work that still needs doing, particularly in interpreting the practical implications.

We echo ICRU's view that the process of adopting the new operational quantities should be carried out over a timescale of decades. This will allow for mature consideration of the changes and for account to be taken of the parallel development of new ICRP recommendations (Clement C *et al*, 2021).

The process of adaptation – whether this is in instrument/ dosemeter development, in calibration laboratory practices, or in radiation protection practice – is likely to be a long one. Stakeholders, especially but not only instrument suppliers, dosemeter suppliers, individual monitoring services and calibration laboratories, should therefore begin work soon, to evaluate and plan for the change.

Authorities should be aware of the potential costs involved in changing to the new quantities. These costs should be evaluated at an early stage.

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