Abstract

The main steps of the calibration of personal dosimeters in terms of the personal dose equivalent \( H_p(10) \) are described. Special consideration is given to ISO photon reference radiations, conversion coefficients from air kerma to \( U_p(10) \), various calibration methods including an example of a routine calibration, and positioning of dosimeters for the calibration. In particular, radiation qualities used for measuring the response as a function of the photon energy and of the direction of the incident radiation in an intercomparison of a Co-ordinated Research Project of the IAEA are dealt with.

1. INTRODUCTION

This paper deals with the calibration of personal dosimeters for photon radiation to be worn on the trunk with respect to the measurand (quantity subject to measurement) personal dose equivalent \( H_p(10) \). \( H_p(10) \) is defined in the body and, for calibration purposes, also in the calibration phantom, a slab phantom. An ideal personal dosimeter for \( H_p(10) \) should have a response with respect to \( H_p(10) \) which does no vary with the energy and directional distribution of incident radiation. When personal dosimeters are calibrated with monodirectional radiation, the angle \( \alpha \) between the direction of incidence of the (calibration) radiation and the reference direction of the personal dosimeter is of importance. In such calibrations, the quantity measured is denoted by \( H_p(10; \alpha) \), or by \( H_p(10; E, \alpha) \) if it is stressed that the quantity is valid only for the photon energy \( E \) (see Figure 1). More general information about calibration, the appertaining terminology and other dosimetric measurands can be found elsewhere [1-10].

In the past air kerma or photon dose equivalent on the front surface of a person was frequently used as the measurand for the dose to be determined for individual monitoring, the personal dose. When changing to the operational quantity personal dose equivalent \( H_p(10) \), much will remain unaltered:

For example, radiation backscattered from the body contributed also to the values of the old measurands. If one compares the value of \( H_p(10) \) with the value of air kerma, \( K_a \), multiplied by the backscatter factor of the trunk at parallel incidence of the radiation from the front (see Figure 2), one can see that the quotient of these two values deviates from unity by less than 25 % above a photon energy of about 25 keV.

Moreover, the measurement point of the personal dose remains a location on the body surface representative of the radiation exposure. This is not even changed by the fact that, now as before, the dosimeter measures at the surface of a person's body while the measured value of \( H_p(10) \) is related to a dose at 10 mm depth inside the person.
FIG. 1. Definition of $H_p(10; E, \alpha)$ for the photon energy $E$ and the angle of incidence $\alpha$ in the slab phantom consisting of ICRU tissue.

FIG. 2. Quotient $H_p(10; E, 0^\circ)/(K_a \cdot B)$ for the ISO water slab phantom for monoenergetic photon radiation as a function of the photon energy $E$. $B$ is the backscatter factor for the ISO water slab phantom [5].
The term *calibration* needs some clarification. *Calibration* is defined in the *International Vocabulary of Basic and General Terms in Metrology* [1]. If the text is applied to a dosimeter as a measuring instrument, the definition of calibration reads: "The set of operations that establish, under specified conditions, the relationship between the quantity indicated by a dosimeter and the corresponding value realised by standards." Three notes are added to the definition:

- The result of the calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.
- A calibration may also determine other metrological properties such as the effect of influence quantities.
- The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

Attention has to be paid also to *routine calibration* because of its importance in practice. A *routine calibration* can be performed, under simplified conditions, either to check the calibration carried out by the manufacturer or to check whether the calibration factor is sufficiently stable during a continued long-term use of the dosimeter. In general, the methods of a routine calibration will be worked out on the basis of the results of a type test, or it may be one of the objectives of a type test to establish the procedures for a routine calibration in such a way that the result of a routine calibration approximates that of a calibration under standard test conditions as closely as possible. A routine calibration is often used to provide batch or individual calibration factors.

The calibration of personal dosimeters on a phantom, which is basically necessary, does not mean that regular routine calibrations cannot be carried out free in air when the performance characteristics of a personal dosimeter are known from a previous test (e.g. a pattern evaluation) which covered irradiations on a phantom and when the characteristics once determined are invariant. The calibration free in air must then be corrected for the influence of the phantom.

A calibration procedure in compliance with ISO standards [2,12] consists of the following steps:

1. Selection of the personal dosimeter to be calibrated. Examination of the dosimeter to confirm that it is in a good serviceable condition and free from radioactive contamination. The set-up procedure and the mode of operation of the dosimeter must be in accordance with its instruction manual.

2. Selection of the calibration conditions, including the radiation type and energy from the series of ISO reference radiations, and of the ISO water slab phantom orientation.

3. Selection of the actual radiation field and the point of test in this radiation field at which the conventional true value of the personal dose equivalent is known.

4. Selection of the calibration method, i.e. calibration against a reference instrument without any monitor or with a monitor; or calibration in a known radiation field.

5. If necessary, establishment of full secondary charged particle equilibrium by means of an additional layer of appropriate material in front of the dosimeter.
6. Positioning of the personal dosimeter with its reference point at the point of test, together with the ISO water slab phantom, both properly oriented in the desired direction, and irradiation of the dosimeter.

7. Computation of the dosimeter's calibration factor or response from the conventional true value of the personal dose equivalent and the value measured by the dosimeter.

This paper deals with the crucial features of the calibration procedure. The ISO photon reference radiations (see step 2) are described with special attention given to the narrow-spectrum series, radiations from radionuclide sources and high-energy photon radiations. These radiations are used in the present "type test" intercomparison of the IAEA. The conversion coefficients necessary to calculate the conventional true value of the personal dose equivalent at the point of test (step 3) are given. Three different methods of calibration (step 4) are explained, and an example of a routine calibration is given. The basic expressions are given for calculating a dosimeter's calibration factor based on an air kerma calibration of the user's reference instrument. Finally, a section is devoted to the positioning of the personal dosimeter at the point of test, including the establishment of secondary charged particle equilibrium (steps 5 and 6).

The term dosimeter is used as a generic term denoting any personal dose or dose rate meter. The term kerma is used to denote air kerma free in air. Detailed definitions of other dosimetric terms are given in a previous paper of the workshop [9].

2. FUNDAMENTALS OF CALIBRATION

2.1. Calibration factor (for reference conditions)

In radiation protection dosimetry the term calibration factor is frequently used in a restricted meaning. When assessing whether a particular dosimeter is adequate for its intended use and before it is used the first time, it is important to have access to reliable type test data of that dosimeter. Each dosimeter should be calibrated before its first use and then be recalibrated periodically. In some countries type test and periodic calibration are already prescribed by law.

The calibration factor is determined under a controlled set of conditions which lie within a range of standard test conditions (e.g. photon energy, angle of radiation incidence, air pressure and temperature, see table in [3, 9]) and its value is corrected for reference conditions (frequently only for air pressure and temperature). This convention assigns unequivocally one calibration factor to a dosimeter, a significant simplification for routine monitoring.

To be consistent with international standards on personal dosimeters, the term calibration factor is defined only for reference conditions.

The calibration factor (for reference conditions), \( N \), is the conventional true value of the quantity the dosimeter is intended to measure, \( H_p(10) \), divided by the dosimeter's reading, the measured value \( M \) (corrected if necessary), under reference conditions. The calibration factor with respect to \( H_p(10) \) is given by:

\[
N = \frac{H_p(10)}{M} \quad (1)
\]
The calibration factor refers to *reference conditions* and shall be determined under conditions which lie within the range of *standard test conditions* recommended in international standards. The conditions under which the determination of the calibration factor was actually carried out shall be specified in the calibration certificate.

To obtain the measured value $M$, as may be prescribed in the dosimeter's instruction manual, it may be necessary, for example, to correct the indicated value $M_i$ for the zero indication $M_0$ and other effects represented by the appropriate correction factors $k_{ci}$:

$$M = (M_i - M_0) \prod_i k_{ci}$$

(2)

The factors $k_{ci}$ are unity for *reference conditions*. The additional index $c$ indicates that this correction factor is specific to the calibration. It should not be confused with other correction factors applied in practice, for example to correct the indicated value of a dosimeter in a well-known radiation field for the energy dependence of the response to obtain a more accurate result (in routine monitoring, however, such a correction is not necessary).

The calibration factor $N$ is dimensionless when the instrument indicates the quantity to be measured. A dosimeter correctly indicating the conventional true value has a calibration factor of unity.

The value of the calibration factor may vary with the magnitude of the quantity to be measured. In such cases a dosimeter is said to have a non-linear response.

To supplement the definition of the calibration factor when determining other metrological properties such as the effect of influence quantities (e.g. photon energy $E$, angle of radiation incidence $\alpha$), the term *response* has been introduced in several international standards. The reciprocal of the calibration factor is equal to the *response* under reference conditions. In contrast to the calibration factor which refers to the reference conditions only, the response refers to any conditions prevailing.

In practice, response divided by the value of the response for the reference radiation quality (relative response) is of particular importance. As an example, the relative response $R$ of a phosphate glass dosimeter with regard to $H_p(10, 0°)$ as a function of the mean photon energy $E$ is shown in Figure 3 [5]. In this case, the response is divided by the value of the response for $^{137}$Cs gamma radiation, the reference radiation quality. The calibration factor is unity for this radiation quality.

The conventional true value of $H_p(10)$ is determined from air kerma (realised by standards) using conversion coefficients (see section 4); thus, $H_p(10)$ is not normally determined directly by means of primary standard measuring devices. The conversion coefficient refers to the slab phantom made of ICRU tissue. Calibrations of personal dosimeters shall be performed on the ISO water slab phantom described in the next chapter.

### 2.2. Phantoms

For calibrations of whole-body dosimeters, ICRU has extended the definition of $H_p(10)$ to a slab phantom made of ICRU tissue equivalent material (*ICRU tissue*), with the dimensions 300 mm × 300 mm × 150 mm [4].
As the ICRU tissue cannot be realized in practice, the personal dosimeters to be calibrated are to be irradiated on the ISO water slab phantom (substitute for the trunk). The ISO water slab phantom has the dimensions 300 mm × 300 mm × 150 mm. It is water filled, the walls are made of polymethyl-methacrylate (PMMA), the front side is 2.5 mm thick, the other sides are 10 mm thick. This phantom is recommended by ISO [2] and has only the function of a backscatter body. Figure 4 shows an example of such an ISO water slab phantom together with a personal dosimeter fastened in the center of the phantom's front surface by means of a holder. The holder consists of a minimum of material (PMMA) to avoid radiation being scattered from the holder into the dosimeter.

In the past, dosimeter irradiations were frequently performed free in air with a typical diameter of the radiation field of about 10 cm; now the diameter of the radiation field on the ISO water slab phantom should be approximately 40 cm to irradiate the whole phantom. As a rule, an increase in the distance between dosimeter and radiation source will be necessary, resulting in a prolongation of the irradiation times by up to a factor 10.

The conversion coefficients for calibrations are calculated using phantoms made of ICRU tissue. For photon radiation, Figure 5 shows a comparison of the backscatter factors of the ISO water slab phantom and of the PMMA slab phantom originally favoured by ICRU, with the backscatter factors of the slab phantom made of ICRU tissue. The backscatter factor of the ISO water slab phantom is much closer to the backscatter factor of the ICRU tissue phantom than that of the PMMA phantom. When the ISO water slab phantom is employed as described
above, no correction factors shall be applied to the dosimeter reading for possible differences between the backscatter properties of the phantom and those of ICRU tissue.

3. PHOTON REFERENCE RADIATIONS

All photon reference radiations shall be chosen from and produced in accordance with ISO Standard 4037-1 [12]. In general, it will be useful to select an appropriate radiation quality, taking into account the specified energy and dose or dose rate range of the dosimeter to be calibrated. For reasons of brevity, short names have been introduced. For X radiation the letters F, L, N, W or H denote the radiation quality, i.e. the fluorescence, the low air-kerma rate, the narrow-spectrum, the wide-spectrum, the high air-kerma rate series, respectively, followed by the chemical symbol of the radiator for the fluorescence X radiation and the generating potential for filtered X radiation. Reference radiations produced by radioactive sources are denoted by the letter S combined with the chemical symbol of the radionuclide; reference radiations produced by nuclear reactions are denoted by the letter R followed by the chemical symbol of the element of the target responsible for the emission of the radiation. Table 1 states all radiation qualities recommended by ISO, together with their mean energies $\bar{E}$ averaged over the fluence spectrum.

Fig. 4. Example of an ISO water slab phantom together with a personal dosimeter fastened in the center of the phantom's front surface.
Each series produces spectra of different resolutions and air-kerma rates. The spectral resolution, $R_E$ (full width at half maximum), is the ratio, expressed as a percentage $(\Delta E / \bar{E}) \cdot 100$ where increment $\Delta E$ is the spectrum width corresponding to half the maximum ordinate of the spectrum. The low air-kerma rate series have the narrowest spectra and lowest air-kerma rates. The high air-kerma rate series produce very wide spectra and the highest air-kerma rates. The narrowest spectra should be used for measurements of the variation of the response of a detector with photon energy, provided that the dose equivalent rates of that series are consistent with the dose equivalent rate range of the instrument under test. The high air-kerma rate series is suitable for determining the overload characteristics of some instruments.

**FIG. 5**. Quotient of the backscatter factor for a slab phantom made of the material $m$, $B(m)$, and that of a slab phantom made of ICRU tissue, $B(\text{ICRU})$. The phantom materials $m$ are water with polymethyl-methacrylate (PMMA) walls (ISO water slab phantom: solid curve) and PMMA (dashed curve) [11]. $E$ is the photon energy.

Typical differences between these ISO series can be recognized, for example, when comparing spectra produced at the same high voltage. Figure 6 shows spectra calculated for the high voltage of 100 kV [13]. The calculations were performed by the semi-empirical program described in [14], a program similar to the program XCOMP5R described in [16]. As no wide spectrum has been recommended by ISO for the high voltage of 100 kV, it is assumed that the filtration for the wide spectrum W-110 produced at 110 kV is adequate for the purpose of this comparison. Table 2 summarizes characteristics of these spectra. It can clearly be seen that dose equivalent rates (expressed by the spectral photon flux per solid angle and tube current, $N_E$) belonging to the spectra, the resolution and the relative contribution of the fluorescent radiation to the dose equivalent rate decrease from the high air-kerma rate spectrum to the low air-kerma rate spectrum. The maximum values of $N_E$ for the narrow spectrum and the low air-kerma rate spectrum in the upper part of Figure 6 are so small that the spectra almost cannot be seen there and are, therefore, magnified in the lower
part of Figure 6 (both parts of the Figure have a linear scale). The decrease of the resolution of the spectra is accompanied by an increase of the mean energy \( \overline{E} \).

The narrow-spectrum series and the reference radiations produced by radionuclide sources and high-energy photon radiations are of particular interest in the "type test" intercomparison of the co-ordinated research project of the IAEA. Their characteristics are given in Tables 3 and 4. The particular spectra used for the supplementary tests are shown in Figure 7.

Details of the operational conditions required to produce the filtered X radiations are also specified in the ISO Standard 4037-1. A typical calibration set-up for the calibration against a reference instrument and a monitor (see section 5.3) is shown schematically in Figure 8. How such a set-up may look in practice is shown in Figure 9. The wheels with the filters used for the computer controlled selection of the filtration of the X radiation can clearly be seen.
TABLE 1. DESIGNATIONS OF THE RADIATION QUALITIES OF THE REFERENCE RADIATION SERIES RECOMMENDED BY ISO, TOGETHER WITH THEIR MEAN ENERGIES

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
<th>Radiation Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-Zn</td>
<td>8.6</td>
<td>L-10</td>
<td>8.5</td>
<td>N-10</td>
<td>8</td>
<td>W-60</td>
<td>45</td>
</tr>
<tr>
<td>F-Ge</td>
<td>9.9</td>
<td>L-20</td>
<td>17</td>
<td>N-15</td>
<td>12</td>
<td>W-80</td>
<td>57</td>
</tr>
<tr>
<td>F-Zr</td>
<td>15.8</td>
<td>L-30</td>
<td>26</td>
<td>N-20</td>
<td>16</td>
<td>W-110</td>
<td>79</td>
</tr>
<tr>
<td>F-Mo</td>
<td>17.5</td>
<td>L-35</td>
<td>30</td>
<td>N-25</td>
<td>20</td>
<td>W-150</td>
<td>104</td>
</tr>
<tr>
<td>F-Cd</td>
<td>23.2</td>
<td>L-55</td>
<td>48</td>
<td>N-30</td>
<td>24</td>
<td>W-200</td>
<td>137</td>
</tr>
<tr>
<td>F-Sn</td>
<td>25.3</td>
<td>L-70</td>
<td>60</td>
<td>N-40</td>
<td>33</td>
<td>W-250</td>
<td>173</td>
</tr>
<tr>
<td>F-Cs</td>
<td>31.0</td>
<td>L-100</td>
<td>87</td>
<td>N-60</td>
<td>48</td>
<td>W-300</td>
<td>208</td>
</tr>
<tr>
<td>F-Nd</td>
<td>37.4</td>
<td>L-125</td>
<td>109</td>
<td>N-80</td>
<td>65</td>
<td>H-280</td>
<td>146</td>
</tr>
<tr>
<td>F-Sm</td>
<td>40.1</td>
<td>L-170</td>
<td>149</td>
<td>N-100</td>
<td>83</td>
<td>H-300</td>
<td>147</td>
</tr>
<tr>
<td>F-Er</td>
<td>49.1</td>
<td>L-210</td>
<td>185</td>
<td>N-120</td>
<td>100</td>
<td>H-200</td>
<td>102</td>
</tr>
<tr>
<td>F-W</td>
<td>59.3</td>
<td>L-240</td>
<td>211</td>
<td>N-150</td>
<td>118</td>
<td>H-250</td>
<td>122</td>
</tr>
<tr>
<td>F-Au</td>
<td>68.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-Pb</td>
<td>75.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-U</td>
<td>98.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radionuclide Series</td>
<td>59.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-Energy Photon Radiation Series</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Reaction</th>
<th>$\bar{E}$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Am $^{241}$Am</td>
<td>$^{12}$C (p,p$\gamma$)$^{12}$C</td>
<td>4.36$^*$</td>
</tr>
<tr>
<td>S-Cs $^{137}$Cs</td>
<td>$^{19}$F (p,$\alpha\gamma$)$^{16}$O</td>
<td>6.61$^*$</td>
</tr>
<tr>
<td>S-Co $^{60}$Co</td>
<td>(n,$\gamma$) capture in Ti</td>
<td>5.14$^*$</td>
</tr>
<tr>
<td>F-Ni</td>
<td>(n,$\gamma$) capture in Ni</td>
<td>6.26$^*$</td>
</tr>
<tr>
<td>F-O</td>
<td>$^{16}$O (n,p)$^{16}$N</td>
<td>6.61$^*$</td>
</tr>
</tbody>
</table>

All mean energies except those for the high-energy photon radiation series are averaged over the fluence spectrum. The mean energies marked by * are averaged over the energy fluence spectrum. For the fluorescence radiation series the energy of the main line of the spectrum is given. Under certain circumstances the use of the lowest energy fluorescence radiations must be avoided for calibrations owing to the effect of the higher energy primary beam radiations scattered from the radiator.
FIG. 6. Comparison of the calculated spectral photon flux per solid angle and tube current, $N_E$, of the low air-kerma rate spectrum L-100, the narrow spectrum N-100, the wide spectrum "W-100" and the high air-kerma rate spectrum H-100. The spectra are calculated for a distance of 2.5 m from a tube with a tungsten anode with an anode angle of 20°. The tube potential is 100 kV. The Figure is split in two parts to allow the four spectra to be presented with linear scales. In the upper Figure the narrow spectrum and the low air-kerma rate spectrum cannot be seen because of their low $N_E$ values.
TABLE II. CHARACTERISTICS OF THE SPECTRA SHOWN IN FIGURE 5. (THE SPECTRAL PHOTON FLUX PER SOLID ANGLE AND TUBE CURRENT, \( N_E \), IS CALCULATED FOR A DISTANCE OF 2.5 M FROM THE TUBE. \( \bar{E} \) IS THE MEAN PHOTON ENERGY AVERAGED OVER THE FLUENCE SPECTRUM. THE FILTRATION OF BE IS THE INHERENT FILTRATION)

<table>
<thead>
<tr>
<th>Filtration</th>
<th>Be</th>
<th>Al</th>
<th>Cu</th>
<th>Sn</th>
<th>( \bar{E} ) in keV</th>
<th>Resolution in %</th>
<th>( N_E ) ( (s^{-1} \text{sr}^{-1} \text{A}^{-1} \text{keV}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>87</td>
<td>22</td>
<td>3.6 ( 10^9 )</td>
</tr>
</tbody>
</table>

TABLE III. CHARACTERISTICS OF THE NARROW-SPECTRUM SERIES. THE TUBE POTENTIAL IS MEASURED UNDER LOAD.

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>( \bar{E} ) keV</th>
<th>Resolution ( R_E ) %</th>
<th>Tube Potential kV</th>
<th>Additional Filtration (mm)</th>
<th>1st HVL mm</th>
<th>2nd HVL mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-10</td>
<td>8</td>
<td>28</td>
<td>10</td>
<td>Pb 0.21 Sn 0.6 Cu 1.0 Al 0.1</td>
<td>0.047 Al</td>
<td>0.052 Al</td>
</tr>
<tr>
<td>N-15</td>
<td>12</td>
<td>33</td>
<td>15</td>
<td></td>
<td>0.14 Al</td>
<td>0.16 Al</td>
</tr>
<tr>
<td>N-20</td>
<td>16</td>
<td>34</td>
<td>20</td>
<td></td>
<td>0.32 Al</td>
<td>0.37 Al</td>
</tr>
<tr>
<td>N-25</td>
<td>20</td>
<td>33</td>
<td>25</td>
<td>0.21</td>
<td>0.66 Al</td>
<td>0.73 Al</td>
</tr>
<tr>
<td>N-30</td>
<td>24</td>
<td>32</td>
<td>30</td>
<td>0.6</td>
<td>1.15 Al</td>
<td>1.30 Al</td>
</tr>
<tr>
<td>N-40</td>
<td>33</td>
<td>30</td>
<td>40</td>
<td>2.0</td>
<td>0.084 Cu</td>
<td>0.091 Cu</td>
</tr>
<tr>
<td>N-60</td>
<td>48</td>
<td>36</td>
<td>60</td>
<td>0.21</td>
<td>0.24 Cu</td>
<td>0.26 Cu</td>
</tr>
<tr>
<td>N-80</td>
<td>65</td>
<td>32</td>
<td>80</td>
<td></td>
<td>0.58 Cu</td>
<td>0.62 Cu</td>
</tr>
<tr>
<td>N-100</td>
<td>83</td>
<td>28</td>
<td>100</td>
<td>1.0</td>
<td>1.11 Cu</td>
<td>1.17 Cu</td>
</tr>
<tr>
<td>N-120</td>
<td>100</td>
<td>27</td>
<td>120</td>
<td>2.5</td>
<td>1.71 Cu</td>
<td>1.77 Cu</td>
</tr>
<tr>
<td>N-150</td>
<td>118</td>
<td>37</td>
<td>150</td>
<td>5.0</td>
<td>2.36 Cu</td>
<td>2.47 Cu</td>
</tr>
<tr>
<td>N-200</td>
<td>164</td>
<td>30</td>
<td>200</td>
<td>0.21</td>
<td>3.99 Cu</td>
<td>4.05 Cu</td>
</tr>
<tr>
<td>N-250</td>
<td>208</td>
<td>28</td>
<td>250</td>
<td></td>
<td>5.19 Cu</td>
<td>5.23 Cu</td>
</tr>
<tr>
<td>N-300</td>
<td>250</td>
<td>27</td>
<td>300</td>
<td></td>
<td>6.12 Cu</td>
<td>6.15 Cu</td>
</tr>
</tbody>
</table>

For the five lowest energies the recommended filtration is 1 mm be but other values may be used provided that the mean energy is within \( \pm 5 \% \) and the resolution is within \( \pm 15 \% \) of the values given in the table. for the higher energies (radiation qualities N-40 and above) the total filtration consists of the additional filtration plus the inherent filtration adjusted to 4 mm of aluminium. the minimum purity of the filters should be 99.9 %. the half value layers (hvl's) are measured at a distance of 1 m from the focal spot.
### TABLE IV. CHARACTERISTICS OF THE REFERENCE RADIATIONS PRODUCED BY RADIONUCLIDE SOURCES AND OF THE HIGH-ENERGY PHOTON RADIATIONS

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Energy of the Radiation (MeV)</th>
<th>Half-Life (days)</th>
<th>Air-kerma Rate Constant mGy h⁻¹.m².MBq⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Co</td>
<td>1.1733 and 1.3325</td>
<td>1925.5</td>
<td>0.31</td>
</tr>
<tr>
<td>S-Cs</td>
<td>0.6616</td>
<td>11050</td>
<td>0.079</td>
</tr>
<tr>
<td>S-Am</td>
<td>0.05954</td>
<td>157788</td>
<td>0.0031</td>
</tr>
<tr>
<td>R-C</td>
<td>4.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-F</td>
<td>6.13 to 7.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-Ti</td>
<td>5.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-Ni</td>
<td>6.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-0</td>
<td>6.13 to 7.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The value of the air-kerma rate constant is valid only for an unshielded point radionuclide source. It is given only as a guide. Air-kerma rates at the exposure positions should be measured using a secondary ionisation chamber. Instead of using sources with different activities, the air-kerma rate may also be varied by means of lead attenuators for collimated beams of ¹³⁷Cs and ⁶⁰Co. The attenuators shall be placed in close vicinity to the diaphragm.

![Relative spectral photon fluence](image)

**FIG. 7. Relative spectral photon fluence $\Phi_E$ of the reference photon radiations used in the "type test" intercomparison of the co-ordinated research project of the IAEA.** The radiation qualities N-40, N-60, N-100 and N-250 belong to the narrow-spectrum series, the radiation quality S-Co to the radionuclide series and the radiation quality R-F to the high-energy photon radiation series. All spectra except the R-F spectrum are theoretical spectra. The R-F spectrum is an unfolded spectrum generated at 2.7 MeV proton energy [15]. In this spectrum the photon radiation generated by an annihilation reaction at 0.51 MeV is omitted for reasons of clarity.
FIG. 8. Scheme of a typical calibration set-up with X radiation for the calibration against a reference instrument and a monitor.

FIG. 9. Example of a calibration set-up with X radiation for the calibration against a reference instrument and a monitor.
4. CONVERSION COEFFICIENT FROM AIR KERMA TO \( H_p(10) \) IN THE ICRU SLAB PHANTOM

In general reference instruments for photon radiation do not directly indicate \( H_p(10; E, \alpha) \) but the air-kerma rate. \( H_p(10; E, \alpha) \) is derived from air kerma \( K_a \) using appropriate conversion coefficients, \( h_{pk}(10; E, \alpha) \), for photon radiation of energy \( E \), with an angle \( \alpha \) between the reference direction of the dosimeter and the direction of radiation incidence:

\[
h_{pk}(10; E, \alpha) = \frac{H_p(10; E, \alpha)}{K_a}
\]

(3)

Tabulated values for \( h_{pk}(10; E, \alpha) \) presuppose the establishment of secondary charged particle equilibrium for the radiation field. An appropriate build-up layer may be required (see section 6.4) resulting in a substitution of \( h_{pk}(10; E, \alpha) \) by \( h_{pk}(10; E, \alpha) \cdot k_{PMMA} \) in eq. (3).

If a reference instrument is used for calibration (denoted by subscript \( R \) in the following), as for the methods given in sections 5.2, 5.3 and 5.5, its calibration factor for air kerma, \( N_R \), given in the calibration certificate can be used to determine the conventional true value of \( H_p(10; E, \alpha) \) by means of the conversion coefficient \( h_{pk}(10; E, \alpha) \) of eq. (3) and the measured (indicated) value \( M_R \) of the reference instrument (corrected for reference conditions):

\[
H_p(10; E, \alpha) = h_{pk}(10; E, \alpha) \cdot N_R \cdot M_R
\]

(4)

For radiation qualities of finite spectral width, the symbol \( E \) is replaced by the relevant letter according to Table I denoting a particular series of reference radiation, i.e. F, L, N, W, H, S or R.

Conversion coefficients \( h_{pk}(10; E, \alpha) \) for monoenergetic radiation shall be treated as if they are not affected by an uncertainty. The conversion coefficients for the narrow-spectrum series, the radionuclide sources and the high-energy photon radiations given in Tables 5 and 6 shall be considered as being affected by a relative standard uncertainty of 2% except those with an exclamation mark. The relative standard uncertainty of 2% takes into account differences between the spectrum used for the calculation of the conversion coefficient [2,12] and that prevailing at the point of test.

The numerical values with an exclamation mark actually applicable to a given experimental set-up may differ by considerably more than 2% from the given value. Such exclamations marks have to be considered only for tube voltages below about 30 kV when photons of low energies may strongly influence the numerical value of the conversion coefficients. Small differences in the energy distribution can result in significant changes in the numerical values of these conversion coefficients as the majority contribution to the air kerma originates from the low-energy part of the spectrum, while the majority contribution to \( H_p(10) \) originates from the high-energy part of the spectrum. Differences between the experimental arrangements as regards the energy distribution may be due to a great number of factors, e.g. anode angle,
anode roughening, tungsten evaporated on the tube window, presence of a transmission monitor chamber in the beam, deviation of the thickness of filters from nominal values, length of the air path between focal spot and point of test, and atmospheric pressure at the time of measurement.

In practice, calibrations are always performed in divergent beams. This is taken into account by relating the conversion coefficients to a reference distance between radiation source and point of test. In cases where a reference distance is given together with an angle $\alpha$ of the direction of radiation incidence, $\alpha$ pertains to the angle between the reference and actual orientation of the dosimeter in the field.

### TABLE V. CONVERSION COEFFICIENT $h_{p\mathcal{K}}(10; N, \alpha)$ FROM AIR KERMA, $K_\alpha$, TO THE DOSE EQUIVALENT $H_p(10; N, \alpha)$ FOR RADIATION QUALITIES GIVEN IN ISO 4037, PART 1 [12] AND THE SLAB PHANTOM, REFERENCE DISTANCE 2 m

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Irr. Dist.</th>
<th>$d_F$ cm</th>
<th>$h_{p\mathcal{K}}(10;N,\alpha)$ in Sv/Gy for Angle of Incidence of</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0°</td>
<td>10°</td>
</tr>
<tr>
<td>N-15 !</td>
<td>1,0 - 2,0</td>
<td>25</td>
<td>0,06</td>
<td>0,06</td>
</tr>
<tr>
<td>N-20 !</td>
<td>1,0 - 2,0</td>
<td>25</td>
<td>0,27</td>
<td>0,27</td>
</tr>
<tr>
<td>N-25 !</td>
<td>1,0 - 3,0</td>
<td>23</td>
<td>0,55</td>
<td>0,55</td>
</tr>
<tr>
<td>N-30</td>
<td>1,0 - 3,0</td>
<td>20</td>
<td>0,79</td>
<td>0,78</td>
</tr>
<tr>
<td>N-40</td>
<td>1,0 - 3,0</td>
<td>16</td>
<td>1,17</td>
<td>1,16</td>
</tr>
<tr>
<td>N-60</td>
<td>1,0 - 3,0</td>
<td>11</td>
<td>1,65</td>
<td>1,64</td>
</tr>
<tr>
<td>N-80</td>
<td>1,0 - 3,0</td>
<td>11</td>
<td>1,88</td>
<td>1,87</td>
</tr>
<tr>
<td>N-100</td>
<td>1,0 - 3,0</td>
<td>11</td>
<td>1,88</td>
<td>1,88</td>
</tr>
<tr>
<td>N-120</td>
<td>1,0 - 3,0</td>
<td>11</td>
<td>1,81</td>
<td>1,80</td>
</tr>
<tr>
<td>N-150</td>
<td>1,0 - 3,0</td>
<td>11</td>
<td>1,73</td>
<td>1,72</td>
</tr>
<tr>
<td>N-200</td>
<td>1,0 - 3,0</td>
<td>12</td>
<td>1,57</td>
<td>1,56</td>
</tr>
<tr>
<td>N-250</td>
<td>1,0 - 3,0</td>
<td>13</td>
<td>1,48</td>
<td>1,48</td>
</tr>
<tr>
<td>N-300</td>
<td>1,0 - 3,0</td>
<td>15</td>
<td>1,42</td>
<td>1,42</td>
</tr>
</tbody>
</table>

The irradiation distance is measured from the focal spot of the x-ray tube to the point of test, at which the reference point of the dosimeter shall be located. The values of the conversion coefficients may be used without modification over the given range of irradiation distances. For radiation qualities with an exclamation mark, care needs to be taken as variations in energy distribution may have a strong influence on the numerical values of conversion coefficients. The meaning of the diameter $d_F$ is explained in Section 6.
5. CALIBRATION METHODS

5.1. General

As stated in section 2, the calibration factor shall be determined under standard test conditions which implies that ISO reference radiations should be used. The first three methods described in this section presume the existence of such reference fields in the calibration laboratory.

However, some laboratories or services have only irradiation facilities differing from those recommended by ISO and, for the time being, have to use this test field for calibrations.

### TABLE VI. CONVERSION COEFFICIENTS $h_{pK}(10; S, \alpha)$ AND $h_{pK}(10; R, \alpha)$ FROM AIR KERMA, $K_a$, TO THE DOSE EQUIVALENT $H_p(10; S, \alpha)$ AND $H_p(10; R, \alpha)$, RESPECTIVELY, FOR RADIATION QUALITIES GIVEN IN ISO 4037-1 [12] AND THE SLAB PHANTOM

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Irr. dist. (m)</th>
<th>$d_F$ (cm)</th>
<th>Build-up Layer (mm)</th>
<th>$k_{PMMA}$</th>
<th>$h_{pK}(10; S, \alpha)$</th>
<th>$h_{pK}(10; R, \alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Am</td>
<td>2.0 - 3.0</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>1.89</td>
<td>1.88</td>
</tr>
<tr>
<td>S-Cs</td>
<td>1.5 - 4.0</td>
<td>15</td>
<td>1.5</td>
<td>1.00</td>
<td>1.21</td>
<td>1.22</td>
</tr>
<tr>
<td>S-Co</td>
<td>1.5 - 4.0</td>
<td>15</td>
<td>4</td>
<td>1.00</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>R-C</td>
<td>1.0 - 5.0</td>
<td>15</td>
<td>25</td>
<td>0.94</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>R-F</td>
<td>1.0 - 5.0</td>
<td>15</td>
<td>25</td>
<td>0.94</td>
<td>1.12</td>
<td>1.12</td>
</tr>
<tr>
<td>T-Ti</td>
<td>1.0 - 5.0</td>
<td>15</td>
<td>25</td>
<td>0.94</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>R-Ni</td>
<td>1.0 - 5.0</td>
<td>15</td>
<td>25</td>
<td>0.94</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>R-O</td>
<td>1.0 - 5.0</td>
<td>15</td>
<td>25</td>
<td>0.94</td>
<td>1.12</td>
<td>1.12</td>
</tr>
</tbody>
</table>

The irradiation distance is measured from the geometrical centre of the radionuclide source to the point of test, at which the reference point of the dosimeter shall be located. In the case of high-energy photon radiations, the irradiation distance shall be measured from the centre of the radiator or target surface from which the radiation emerges to the point of test. The values of the conversion coefficients may be used without modification over the given range of irradiation distances. The meanings of the diameter $d_F$, the build-up layer and the correction factor $k_{PMMA}$ are explained in Section 6.

An example of such a test field is a photon radiation field generated by a $^{137}$Cs source operated in a small room so that radiation scattered from the walls makes a remarkable contribution to the air-kerma rate at the reference point, say 20%. The application of eq. (3) in section 4 using a value of the air-kerma rate measured by a reference instrument and the conversion coefficient from Table 6 would produce a faulty result as:
the detector of the reference instrument for the air-kerma rate probably is an ionisation chamber with an almost isotropic angular response to air kerma measuring the air kerma not only of the collimated beam but also of the radiation scattered from all directions of the room, i.e. even of that backscattered radiation which does not contribute to the indication of a personal dosimeter fastened on a phantom because this scattered radiation is shielded by the phantom;

- the conversion coefficient from Table VI refers to pure $^{137}\text{Cs}$ radiation only, i.e. collimated beam conditions are presumed.

Another example of a test field is a field of high-energy beta radiation emitted by a beta source (e.g. of the radionuclide $^{90}\text{Y}$). This radiation may not even be a type of radiation which the dosimeter is intended to measure.

It is essential that the correspondence of the dosimeter's reading in the test field to the reading of the dosimeter in a reference field is established, and that this correspondence, once determined in a type test, is invariant. In this case, a routine calibration with, of course, less than the highest metrological quality can be carried out in such a test field. Considering the importance such routine calibrations have in practice, it is shown in section 5.5 by an example how such a test field can be used.

5.2. Calibration with a reference instrument without any monitor

This procedure is appropriate if the value of the air-kerma rate is stable over a time period corresponding to the duration of the calibration so as to achieve results of the desired accuracy. The calibration is carried out under standard test conditions close to the reference conditions. The calibration set-up is shown schematically in the upper half of Figure 10. The reference points of the reference instrument and the dosimeter under calibration are subsequently positioned at the point of test in the radiation field for calibration in terms of $H_p(l_0;E,\alpha)$. The position of the point of test is determined by the intersection of the dashed lines in Figure 10.

**Part 1 of the Figure:** For the reference instrument (subscript $R$) one obtains the calibration factor $N_R$ of the reference instrument (under reference conditions) from the measured (indicated) value $M_R$ of the reference instrument corrected for reference conditions by means of eq. (4):

$$
N_R = \frac{H_p(l_0;E,\alpha)}{h_{pk}(10;E,\alpha) \cdot M_R}
$$

$h_{pk}(10;E,\alpha)$ is the coefficient to convert from air kerma measured by the reference instrument to $H_p(l_0;E,\alpha)$. Depending on the radiation quality used, the energy $E$ has to be replaced in eq. (5), and consequently in the following equations, by F, L, N, W, H, S or R (see section 3).
**Part (2) of the Figure:** The dosimeter under calibration (subscript I) has an indication directly related to the dose equivalent quantity $H_p(10; E, \alpha)$. The dosimeter is positioned on the ISO water slab phantom with an angle $\alpha$ between the axis of the reference radiation field and the reference direction of the personal dosimeter; most frequently $\alpha = 0^\circ$ will be chosen. The dosimeter’s calibration factor (under reference conditions) $N_I$ is obtained from the measured (indicated) value, corrected for reference conditions, $M_I$:

$$N_I = \frac{H_p(10; E, \alpha)}{M_I}$$  \hspace{1cm} (6)

The combination of eqs. (5) and (6) results in the calibration factor $N_I$ derived from $N_R$:

$$N_I = N_R \cdot \frac{h_{pK}(10; E, \alpha) \cdot M_R}{M_I}$$  \hspace{1cm} (7)

**5.3. Calibration with a reference instrument and with a monitor**

Moderate variations in the course of time in the physical quantities that characterize the dosimetric properties of the radiation field (e.g. air-kerma rate) can be corrected by using a monitor and by irradiating the reference instrument and the personal dosimeter under calibration sequentially. This technique is often employed with X-ray units in order to correct for variations in the air-kerma rate when reference instrument and dosimeter under calibration are alternately placed at the point of test. The calibration set-up is schematically shown in the lower part of Figure 10 in a way similar to that chosen for the calibration set-up in the previous chapter. The reference points of the reference instrument and the dosimeter under calibration are subsequently positioned at the point of test in the radiation field for calibration in terms of $H_p(10; E, \alpha)$.

Its value at the point of test is related to the calibration factor of the monitor chamber, $N_M$, and its measured (indicated) value $m$ by

$$N_M = \frac{H_p(10; E, \alpha)}{m}$$  \hspace{1cm} (8)

**Part (1) of the Figure:** The calibration factor $N_R$ of the reference instrument (under reference conditions) is

$$N_R = \frac{H_p(10; E, \alpha)}{h_{pK}(10; E, \alpha) \cdot M_R}$$  \hspace{1cm} (9)

where $M_R$ is the measured (indicated) value of the reference instrument corrected for reference conditions (i.e. indication multiplied by applicable correction factors, e.g. a correction factor considering differences in air density).
Calibration with a reference instrument without any monitor

\[ N_i = N_R \cdot \frac{h_{pk}(\theta; F, \alpha) \cdot M_R}{M_i} \]

Calibration with a reference instrument and with a monitor

\[ N_i = \frac{N_R \cdot h_{pk}(\theta; F, \alpha) \cdot M_R}{m_i} \cdot \frac{m_i}{M_i} \]

**FIG. 10.** Calibration with a reference instrument (schematically).
Part (2) of the Figure: The corresponding equation for the calibration factor $N_I$ of the dosimeter (under reference conditions) is:

$$N_I = \frac{H_p(10; E, \alpha)}{M_I}$$  \hspace{1cm} (10)

$M_I$ is the respective value of the dosimeter under calibration.

$H_p(10; E, \alpha)$ can be eliminated in eqs. (9) and (10) by means of eq. (8) if one introduces the measured values $m_R$ and $m_I$ of the monitor for the irradiation of the reference instrument and the dosimeter under calibration:

$$N_R = \frac{N_M m_R}{h_{PK}(10; E, \alpha) M_R}$$  \hspace{1cm} (11)

$$N_I = \frac{N_M m_I}{M_I}$$  \hspace{1cm} (12)

$m_R$ is the measured (indicated) value of the monitor for the irradiation of the reference instrument, corrected for reference conditions (i.e. indication multiplied by applicable correction factors, e.g. differences in air density) and $m_I$ the corresponding value of the monitor for the irradiation of the dosimeter.

By division of eqs. (11) and (12), the calibration factor $N_M$ disappears and one obtains for the calibration factor of the dosimeter (under reference conditions) $N_I$:

$$N_I = N_R \left( \frac{h_{PK}(10; E, \alpha) M_R}{m_R} \right) \left( \frac{m_I}{M_I} \right)$$  \hspace{1cm} (13)

In practice, if the irradiations of reference instrument and dosimeter to be calibrated are performed in brief succession, the ambient conditions of the radiation monitor remain the same and corrections of the indicated value of the monitor to reference conditions are unnecessary.

In cases where the monitor is of good long-term stability, it may serve as the reference instrument after having been calibrated against another reference instrument.
5.4. Calibration in a known radiation field

For a radiation field in which the conventional true value of $H_p(10; E, \alpha)$ at the point of test is directly known, the calibration factor $N_I$ of the dosimeter is obtained from its measured value, corrected for reference conditions, $M_I$ (see Figure 11):

$$N_I = \frac{H_p(10; E, \alpha)}{M_I} \quad (14)$$

5.5. Example of a routine calibration

It is assumed that a service has established a test field with a $^{137}\text{Cs}$ source for routine calibrations of dosimeters as described in section 5.1. This test field is used in connection with occasional calibrations in a reference field of a secondary standard laboratory. The correspondence must be established between the dosimeter's reading in the test field and the reading of the dosimeter in the reference field, and it must be shown that this correspondence is invariant. Routine calibrations will be needed for new batches of dosimeters and for routine checks of the reproducibility of the dosimeter evaluation. In this example, a three step procedure is followed by the service (see Figure 12).
Calibration of the dosimeter in the reference field: \( N_{\text{ref}} = H_p(10; E_{\text{ref}}, \alpha_{\text{ref}}) / M_{\text{ref}} \)

Transfer of the calibration to the test field: \( H_{p,\text{test}}(10; E_{\text{test}}, \alpha_{\text{test}}) = M_{\text{test}} \cdot N_{\text{ref}} \)

Routine calibration in the test field: \( N_{\text{test}} = H_{p,\text{test}}(10; E_{\text{test}}, \alpha_{\text{test}}) / M_{\text{test}} \)

**FIG. 12.** Example of a routine calibration with three experimental set-ups (schematically).
Step 1. For simplicity it is assumed that one routine dosimeter is sent by the service to a secondary standard laboratory; if more dosimeters are sent in, appropriate mean values of the measured values have to be taken into account. In the secondary standard laboratory the irradiation is performed on an ISO water slab phantom in the reference field, for which the conventional true value of $H_{p \text{ref}}(10; E_{\text{ref}}, \alpha_{\text{ref}})$ is known at the point of test. According to eq. (14), the calibration factor $N_{1 \text{ref}}$ is obtained from the measured value, corrected for reference conditions, $M_{1 \text{ref}}$:

$$N_{1 \text{ref}} = \frac{H_{p \text{ref}}(10; E_{\text{ref}}, \alpha_{\text{ref}})}{M_{1 \text{ref}}}$$  \hspace{1cm} (15)

Step 2. After return to the service, the calibrated dosimeter is irradiated homogeneously at a certain point (point of test) in the test field where the measured value, corrected for reference conditions, $M_{\text{test}}$, is obtained. This can be formally associated with a dose equivalent $H_{p \text{test}}(10; E_{\text{test}}, \alpha_{\text{test}})$ if one assumes the validity of the calibration factor of the reference field, $N_{1 \text{ref}}$:

$$H_{p \text{test}}(10; E_{\text{test}}, \alpha_{\text{test}}) = M_{\text{test}} \cdot N_{1 \text{ref}}$$  \hspace{1cm} (16)

Here the routine dosimeter plays the role of a reference instrument. It links the quantity $H_{p \text{test}}(10; E_{\text{test}}, \alpha_{\text{test}})$ of the test field with $H_{p \text{ref}}(10; E_{\text{ref}}, \alpha_{\text{ref}})$ in the reference field even if the dosimeter is not irradiated on a phantom.

Step 3. This step 3 is the routine calibration in the true sense of the word. Subject is any (routine) dosimeter of the same type as the dosimeter calibrated in the reference field (step 1). The calibration factor $N_{\text{rout}}$ of the (routine) dosimeter is obtained at the point of test in the test field from the the measured value, corrected for reference conditions, $M_{\text{rout}}$, and the dose equivalent $H_{p \text{test}}(10; E_{\text{test}}, \alpha_{\text{test}})$ determined in step 2:

$$N_{\text{rout}} = \frac{H_{p \text{test}}(10; E_{\text{test}}, \alpha_{\text{test}})}{M_{\text{rout}}}$$  \hspace{1cm} (17)

It is obvious that this routine calibration is, in principle, of less metrological quality than a calibration based on one of the methods described in sections 5.2 to 5.4 because a routine dosimeter of inferior performance is used as a reference instrument in step 1. Moreover, the assumption that the calibration factor $N_{1 \text{ref}}$ is valid for the test field has to be checked (compare eq. (16)). This assumption is questionable, for example, if the reading in the reference field is primarily generated by the backscatter of the phantom and the calibration in the test field is performed free in air.
6. POSITIONING OF THE PERSONAL DOSIMETER

6.1. Reference point and point of test

For the calibration the reference point of the dosimeter has to be placed at the so-called point of test in the radiation field at which the conventional true value of $H_p(10)$ is known. The reference point and the reference direction of the dosimeter should be stated by the manufacturer. The reference point should be marked on the outside of a dosimeter. If this proves impossible, the reference point should be indicated in the accompanying documents supplied with the dosimeter. All distances between the radiation source and the dosimeter shall be taken as the distance between the radiation source and the dosimeter's reference point.

In the absence of information on the reference point or on the reference direction of the dosimeter to be calibrated, these parameters shall be fixed by the calibrating laboratory. They shall be stated in the calibration certificate.

When the angular dependence of the response has to be measured, in a first step, the dosimeter is fastened on the phantom's front surface so that the dosimeter's reference direction coincides with the normal on the phantom's front surface (Figure 13). Then the dosimeter's reference point and the point of test in the radiation field are brought into coincidence and, finally, the combination of dosimeter and phantom is rotated about an axis passing through the reference point of the dosimeter so that the reference direction of the dosimeter and the direction of radiation incidence of the irradiation facility form the desired angle $\alpha$.

The calibration factor is determined under conditions lying within the range of standard test conditions which usually means $\alpha = 0^\circ$.

---

**FIG. 13. Arrangement for the calibration and the measurement of the response of a personal dosimeter at the angle $\alpha$.**
6.2. Simultaneous irradiations of dosimeters

When several personal dosimeters are irradiated simultaneously on the front face of the slab phantom they shall not cover any phantom surface outside a circle of diameter $d_F$, given by the approximate locus of the 98% isodose contour with respect to the dose in the centre of the phantom. The values of $h_{pk}(10; N, \alpha)$ depend on the radiation quality and they are given for some reference radiations in Tables V and VI. If irradiation distances smaller than those given in the Tables are used, the diameter $d_F$ becomes smaller.

Two effects associated with this (simplified) procedure require additional attention:

- by positioning several dosimeters on the phantom surface the backscatter may be reduced due to the attenuation of the primary radiation passing through the dosimeters and
- possibly different distances of the reference points from the radiation source have to be considered.

Before such a practice is adopted it shall be verified that it leads to results identical to within 2% to those obtained when only one dosimeter is irradiated in the centred position.

There may be certain types of dosimeters which respond very sensitively to small changes in the properties of the backscattered photon field. This may be due to the use of strongly energy-dependent detectors or possibly, to the properties of the algorithms used to arrive at the value of the dose equivalent from the detector signal. In such cases it may be advisable to have only one dosimeter mounted on the phantom surface for any calibration.

6.3. Misplacement and dosimeter supports

In the case of point sources and in the absence of scattered radiation and photon absorption, the dose rate changes with the inverse square of the distance $R$. A misplacement of the dosimeter's reference point in the beam by the amount of $\Delta R$ in the direction of the beam will lead to a relative error in the calibration factor of $2\Delta R/R$ at the distance $R$. Misalignment perpendicular to the beam axis by $\Delta\rho$ causes a relative error of $(\Delta\rho/R)^2$. In the presence of scattered radiation and for sources of finite dimensions, the above approximations are limited to values of $\Delta R$ or $\Delta\rho$ small in comparison with $R$.

The supports used for the dosimeter and the reference instrument, and the calibration source should introduce as little scattered radiation as possible. The effects of such scattered radiation on the indication of the instruments should be taken into account.

6.4. Effects associated with electron ranges

In some photon fields, effects associated with electron ranges have to be considered. For dosimeters being calibrated there is no secondary electronic equilibrium within the sensitive volume of their detectors. In some cases, the detector window or encapsulation is not sufficiently thick for dose build-up, one prerequisite for secondary electronic equilibrium. For those dosimeters one would obtain different indications in photon radiation fields with differing electronic equilibrium. By placing a layer in front of the detector, which together with the wall material and the cover of the detector gives a combined layer of a thickness larger than the range of the most energetic secondary electrons, one is able to obtain reproducible results. Experience has shown that one does not require any additional layers for photon energies below 250 keV; up to 0.66 MeV, a layer of PMMA 1.5 mm thick is
sufficient. For energies up to 1.33 MeV, a 4 mm PMMA layer is sufficient. The cross-sectional area of the plate shall be 30 cm x 30 cm.

The modification of the radiation field by introducing the PMMA plate shall be taken into account by multiplying the conversion coefficient by the correction factor \( k_{\text{PMMA}} \) (see Table 6).

For irradiations on a phantom it may be practical to position the PMMA plate at a certain distance away from the dosimeter or dosimeter-phantom combination so that it is not necessary to also rotate the plate when the variation of response with the direction of radiation incidence is examined.

**REFERENCES**


[10] GRIFFITH, R., Quantities and Units for External Dose Assessment. This publication.


