Experimental and Monte Carlo Studies on the calibration of photon personal dosemeters in terms of $H_p(3)$

E. Fantuzzi, G. Gualdrini, P. Ferrari, R. Bedogni, F. Monteventi, B. Morelli, F. Mariotti

ENEA - ION-IRP, V. dei Colli 16, I-40136 Bologna, Italy
E-mail: fantuzzi@bologna.enea.it, guald@bologna.enea.it

Abstract. The present paper briefly summarizes the main aspects of a study carried out at ENEA-Radiation Protection Institute (Bologna-Italy) to provide practical procedures for the calibration of dosemeters in terms of $H_p(3)$. Two aspects are connected to this topic: the definition of the quantity itself and the calibration procedures. The $H_p(d)$ was originally defined on ICRU report 51 as the dose equivalent in soft tissue, at an appropriate depth $d$ (mm), below a specified point on the body and $H_p(3)$ is recommended for eye lens dosimetry. Corresponding sets of conversion coefficients between physical quantities (e.g. fluence or air kerma) and the operational quantity $H_p(d)$ were calculated on a $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$ tissue equivalent slab phantom and reported on ICRP 74 and ICRU 57 reports. For the calibration of the dosemeters an ISO $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$ PMMA water filled phantom is employed. This approach, originally defined for the trunk, is generally adopted also for the eye lens dosimetry. These two aspects (quantity calculation and dosemeter calibration in terms of $H_p(3)$) are critically discussed in the work, relying on experimental measurements and Monte Carlo simulations.

1. Introduction

The ICRU recommendations (ICRU-47 [1] – ICRU-51 [2], etc.) define the “Personal Dose Equivalent $H_p(d)$” for individual monitoring practice. This quantity is associated to three standard depths, i.e., 0.07 mm for the skin, 3 mm for the eye lens and 10 mm for the whole body. The air kerma to personal dose equivalent conversion coefficients for $H_p(3)$ and $H_p(10)$ were obtained through Monte Carlo simulations on a simplified $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$, 4-element, ICRU tissue equivalent slab phantom. The set of conversion coefficients for trunk, for 10 mm and 0.07 mm depth are reported on ICRP-74 [3] and ICRU-57 [4], whilst $H_p(3)/ka$ values were never officially published in ICRP or ICRU reports and could be only find in a GSF Report by Till et al [5].

According to the ISO recommendations [6], a rod calibration PMMA phantom is required for the finger and a pillar PMMA phantom for the wrist and ankle dosimetry, whilst a $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$ water filled PMMA phantom is indicated to calibrate whole body dosemeters in terms of $H_p(10)$. The same slab phantom was suggested by ISO 12794 [7] for calibrating personal dosemeters in terms of $H_p(3)$ for the eye lens monitoring.

In the radiological protection practice the quantity $H_p(3)$ is scarcely applied and usually its estimate is carried out from a mathematical combination of the $H_p(0.07)$ and $H_p(10)$ estimated values. This is at the moment the technique applied at the ENEA-Radiation Protection Institute [8].

The work outlined in the present paper is based on both experimental and Monte Carlo studies carried out on a series of irradiation scenarios, with ISO reference X-ray radiation fields. The study was addressed to a critical analysis of the energy tests and calibration of personal dosemeters in terms of $H_p(3)$:

Is a $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$ ICRU 4-element tissue equivalent slab phantom suitable to model $H_p(3)$?

Is a $30\,\mathrm{cm} \times 30\,\mathrm{cm} \times 15\,\mathrm{cm}$ water filled PMMA phantom suitable for the calibration of personal dosemeters in terms of $H_p(3)$?

This general study should contribute to evaluate the accuracy of the eye lens monitoring in the radiation protection practice.
2. Materials and methods

In order to answer to the previous questions it should be decided at what extent the recommended 30 cm × 30 cm × 15 cm ICRU slab phantom is suitable for Hp(3) evaluation, testing the performances of alternative phantoms. A reduced 20 cm × 15 cm × 20 cm 4-elements tissue equivalent slab phantom, that could better fit a human head, was therefore adopted as a first working hypothesis and a new set of conversion coefficients was calculated by the Monte Carlo code MCNP(ver 4c) [9].

A series of measurements was carried out on a corresponding PMMA water filled phantom to evaluate its backscatter performance.

The calculations of the conversion coefficients Hp(3)/ka for a modified 4-element ICRU tissue 20 cm × 15 cm × 20 cm were performed by MCNP for a series of monoenergetic photon beams ranging from 10 keV to 10 MeV.

On the other hand air kerma backscatter factor evaluations were performed for the ISO Narrow Spectrum Series (from 40 kV to 300 kV) for 0° incidence angle, to evaluate the backscatter contribution in the calibration phantom. Numerical spectra for the ISO Narrow Spectrum Series were taken from Laitano et al.[10].

Calculation have been performed for three practical phantoms: the 30 cm × 30 cm × 15 cm water filled PMMA slab phantom, a reduced 20 cm × 15 cm × 20 cm PMMA water filled phantom (more similar in “shape” and dimension to a real head) and a head phantom, whose mathematical description was taken from ADAM [11]. This could provide information on the adequacy of the two slab phantoms (ISO standard and the smaller modified one) for the eye lens dosimetry in terms of Hp(3).

Experimental evaluations of the air kerma backscatter factors on the two PMMA water filled phantoms and the Alderson anthropomorphic plastic phantom were carried out at the ENEA IRP Secondary Standard Calibration Laboratory. The irradiation tests were performed under normal incidence condition, using the reference X-rays beams from the ISO Narrow Spectrum Series, namely 12 beams in the range 15 kV ÷ 300 kV.

The air kerma measurements in phantom-present condition were adjusted taking into account the response of the instrument to the backscattered radiation, whose spectrum was previously evaluated through Monte Carlo modelling. For the X-ray beams from 15 to 40 kV, the thin wall ion chamber Keithley 96035 (wall thickness = 0.075 g·cm⁻², volume = 15 cm³) was employed, whilst for the beams from 40 to 300 kV the O.F.S. TK-30 ion chamber was used (wall thickness = 0.3 g·cm⁻², volume = 30 cm³). Both the ion chambers are traceable to the standards of the Italian National Metrology Institute. The measurements were carried out by placing the chambers at contact with the phantom surface, namely in the centre of the front face of the slabs and in the centre of the forehead of the Alderson phantom. The uncertainties associated to the backscatter factor are of the order of 1% (at 95% confidence level).

3. Hp(3) quantity - theoretical considerations

A discussion on the operational quantity Hp(3) should be based on a comparison with the Quantity, Equivalent Dose to the eye lens, HT(eye lens), as defined in the ICRP-74 and ICRU-57 documents. The quantity was evaluated for the two eyes as described in the ADAM phantom, based on the MIRD analytical human phantom. In the anthropomorphic phantom the eyes are correctly placed symmetrically and externally, aside the nose. The Hp(3) operational quantity defined at 3 mm depth below the centre of the face of a 30 cm × 30 cm × 15 cm tissue equivalent slab phantom is therefore expected to overestimate HT(eye lens) due to two main reasons:

1- The ICRU slab phantom is representative of the trunk and not of the head and therefore it provides higher scattered contribution to the operational quantity compared with the case of the radiation protection quantity (see Fig. 1).

2- In the ICRU slab phantom the operational quantity is calculated at the centre of the phantom whilst in the ADAM head the two eye sensors are placed towards the periphery of
the phantom. This implies again a very significant overestimation for the Hp(3) operational quantity compared with HT(eye lens) (see Fig. 2).

The above considerations justify the proposal of a phantom reduced in dimension to define the operational quantity (see Hp(3)/Ka on reduced slab phantom curve in Fig. 1).

FIG. 1. \(Hp(3)/Ka\) for the two investigated theoretical phantoms compared with \(HT\) (Eye Lens)/Ka [the values for the 30x30x15 cm\(^3\) phantom are taken from GSF results]. Monte Carlo errors are less than 1% (at 95% confidence level).

FIG. 2. Anterior-posterior irradiation at 100 keV. Spatial behaviour of \(Hp(3)/Ka\) from phantom face centre to the periphery.

4. Energy tests and calibrations

A second discussion should focus on the energy tests and calibration conditions. The backscattering performance of the adopted calibration phantom should be compared with backscattering properties at the detection point during routine measurements, assuming that the dosemeter could be worn on the forehead.
Fig. 3 reports of the air kerma backscatter factors for the three investigated phantoms. The results of the experimental measurements are also reported. It should be pointed out that the Monte Carlo model is an exact representation of the two PMMA water filled phantoms, whilst a compromise for the head model had to be accepted (the ADAM head is only a very simplified approximation of the Alderson head phantom). This modelling limitations can explain the discrepancies between Monte Carlo and experimental values for anthropomorphic phantom. A satisfactory agreement between the numerical and experimental results should be noticed for the reduced water filled phantom, whilst a systematic overestimation of about 3% for the Monte Carlo results occurs in the case of ISO slab phantom, that should be investigated.

The reduced 20 cm × 15 cm × 20 cm phantom seems to be a better approximation of the anthropoid phantom also for its backscattering characteristics.

![Graph showing backscatter factors](image)

**FIG.3.** Narrow spectrum series - Behaviour of the Air Kerma Backscatter Factors as a function of beam mean energy for two practical slab phantoms and the two anthropoid head (analytical and Alderson) phantoms

5. Conclusions

The Monte Carlo and experimental investigations carried out in the present work demonstrate that the adoption of a phantom representative of the human trunk could be somewhat questionable both to define \( H_p(3) \) and to carry out type test of calibrations of personal dosemeters. On one hand, the introduction of a different phantom for the calculation of the \( H_p/ka \) conversion coefficients can be rather easy and the associated computational efforts could be of scarce relevance. On the other hand, the adoption of a more realistic (reduced) calibration phantom for \( H_p(3) \) would be cost effective and the proposed 20 cm × 15 cm × 20 cm slab phantom seems to be a first satisfactory solution.

Further investigations are underway both relying on Monte Carlo simulations and experimental measurements, to provide a complete set of data both for the conversion coefficients and for the backscatter factors in terms of energy and angle dependence. Preliminary results about angle dependence demonstrate the better adequacy of the proposed reduced phantom.

These results encourage the adoption of new criteria in the eye lens exposure dosimetry field.
6. References

5. Till E., Zankl M., Drexler G. Angular Dependence of Depth Doses in a Tissue Slab Irradiated with Monoenergetic Photons, GSF Report GSF-Bericht 27/95
7. International Organisation for Standardisation Individual thermoluminescence dosemeters for extremities and eyes ISO 12794