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Uncertainty Analysis of $H_p(10)_{meas}/H_p(10)_{del}$ Ratio for TLD-100H at Energy 24-1250 keV

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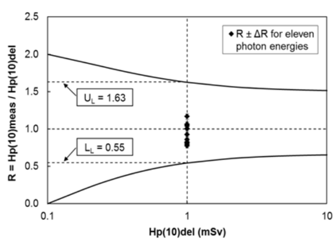
Graphical abstract



Abstract

The $H_p(10)$ of an ideal TLD is independent of photon energy. This is to say that at any photon energy, the ratio R of the measured dose $H_p(10)_{meas}$ to the delivered dose $H_p(10)_{del}$ is always 1. In practice however the $H_p(10)$ is dependent on the energy and R is not equal to 1. For this reason, ICRP has set the lower limit L_L and upper limit U_L for R as $0.55 \leq R \leq 1.63$ for detection limit of 0.1 mSv and $H_p(10)_{del}$=1 mSv. As R is the quantity arises from the measurement processes, the existence of uncertainty of R, i.e. ΔR is inevitable. In the boundary cases, such as when R is slightly lower than L_L or slightly larger than U_L, ΔR would serve a useful quantity in decision making either to accept or to reject the value of R. The purpose of the present work is to estimate ΔR for the TLD-100H for photon energy of 24-1250 keV. The estimation of ΔR is based on the error propagation method. For the eleven photon energies, this work obtained (a) R in the range of 0.77 to 1.16, (b) ΔR in the range of ± 0.02 to ± 0.04. The values of R were satisfactory as they complied the ICRP limit. The determined ΔR is considered very small as it is in the order of 3% in comparison of R.

Keywords: Energy dependence; $H_p(10)$ uncertainty; ICRP trumpet graph; TLD-100H

Abstrak

$H_p(10)$ sebuah TLD yang ideal tidak bergantung kepada tenaga. Dengan kata lain, pada tenaga foton tertentu, nisbah dos diukur $H_p(10)_{meas}$ kepada dos diberi $H_p(10)_{del}$ selalu 1. Walau bagaimanapun, pada kenyataannya $H_p(10)$ adalah bergantung kepada tenaga dan nisbahnya tidak sama dengan 1. Untuk ini ICRP telah menetapkan had bawah L_L dan had atas U_L untuk R sebagai $0.55 \leq R \leq 1.63$ untuk had pengesanan 0.1 mSv dan $H_p(10)_{del}$=1 mSv. Disebabkan R adalah satu kuantiti berasal dari proses pengukuran, kewujudan ketidakpastian R, iaitu ΔR tidak dapat dielakkan. Untuk kes sempadan, seperti bila R hanya kecil sedikit dari L_L atau besar sedikit dari U_L, ΔR dapat berfungsi sebagai satu kuantiti berguna dalam membuat keputusan sama ada untuk menerima atau menolak nilai R. Tujuan kerja ini hendak menganggarkan ΔR untuk TLD-100H bagi tenaga foton 24-1250 keV. Penganggaran ΔR dikira berdasarkan kaedah penjanaan ralat. Untuk sebelas tenaga foton, kerja ini mencatatkan (a) R dalam julat 0.77 hingga 1.16, (b) ΔR dalam julat ± 0.02 hingga ± 0.04. Nilai R didapati memuaskan kerana ia memenuhi keperluan had ICRP. ΔR yang ditentukan dianggap sangat kecil kerana ia berada dalam tertib 3% jika dibandingkan dengan in R.

Kata kunci: Kebergantungan tenaga; ketidakpastian $H_p(10)$; graf trumpet ICRP; TLD-100H

1.0 INTRODUCTION

Deep dose, estimation of effective dose or whole body dose at a depth of 10 mm are a few names used to describe the quantity of $H_p(10)$. But the lengthy description given by the ICRU [1-3] is the personal dose equivalent in ICRU soft tissue at a depth of 10 mm in the body at the location where personal dosemeter is worn. As this quantity is measured by the TLD, the accuracy of the measured $H_p(10)$ i.e. $H_p(10)_{meas}$ in comparison with the delivered $H_p(10)$ i.e. $H_p(10)_{del}$ is controlled by a trumpet graph [4]. In a mathematical form, this graph is represented by the following equation [5], where D_L is the TLD detection limit.

$$\left(\frac{1}{1.5}\right)\left[1-\frac{2D_L}{D_L+H_p(10)_{del}}\right] \leq \frac{H_p(10)_{meas}}{H_p(10)_{del}} \leq (1.5)\left[1+\frac{D_L}{2D_L+H_p(10)_{del}}\right] \quad (1)$$

Replacing the terms on the left-hand-side (the lower limit), the middle (the ratio) and the right-hand-side (the upper limit) with L_L, R and U_L symbols, equation (1) becomes

$$L_L \leq R \leq U_L \quad (2)$$

The values of L_L and U_L are determined by D_L. By taking D_L = 0.1 mSv and $H_p(10)_{del}$ = 1 mSv, equation (2) now becomes

$$0.55 \leq R \leq 1.63 \quad (3)$$

Equation (3) states that for a given delivered dose, the measured dose is accurate if ratio of the measured dose to the delivered dose is larger than 0.55 and smaller than 1.63.

There was a report [6] for example on cases where R did not fulfill the accuracy criteria given by equations (1)-(3). When such a case arises, one shouldn't simply jump into conclusion that the measured $H_p(10)$ is inaccurate, without first doing the statistical analysis, such as examining the uncertainty in R and the use confident interval. It is expected that this might be a case as emphasizes on the estimation of R is not given by the ICRP trumpet graph.

2.0 MATERIALS AND METHODS

The two-element Harshaw TLD-100H (as shown in Figure 1) were used to measure $H_p(10)$. The list of all the equipments used in this work are described in Table 1 [7, 8]. In the following section, the method to get all the quantities as summarized in Table 2 will be described. Basically, the uncertainty of this quantity is determined based on the error propagation method described elsewhere [9].

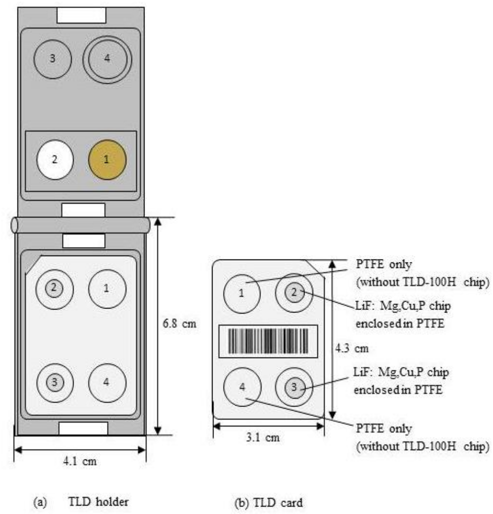


Figure 1 The two-element Harshaw TLD-100H. The element 2 is for measuring $H_p(10)$

Table 1 Equipments used in this study

Equipment	Model	Manufacturer	Remarks
X-ray machine	ISO narrow beam X-ray spectrum	-	The lower photon energies of 24, 32, 47, 65, 84, 100, 121, 171 and 218 keV
Gamma radiation machine	OB 85/1(#873)	Steuerungstechnik & Strahlenshutz GmbH	^{137}Cs 662 keV, ^{60}Co 1250 keV
Ion chamber	M320002(#013)	Physikalisch Technische Wekstatten	Active volume: 1000 cc
TLD chip	TLD-100H	Harshaw	Material LiF: Mg, Cu, P Ø=3.6mm, thickness: 0.25mm
TLD card and holder	TLD-0110H	Harshaw	Card: 6.8 × 4.1 cm^2 Holder: 4.1 × 3.1 cm^2
TLD reader	Harshaw 4500	Thermo Electron Co.	To read the TLD charge
Analysis software	WinREMS	Saint-Gobain Crystals & Detectors	
Water phantom	-	IAEA	Volume: 30 × 30 × 15 cm^3
Thermometer & gyrometer	-	-	To measure the temperature and pressure of the experiment

2.1 Determination of $H_p(10)$ Calibration Coefficient of the TLD card, $C_f \pm \Delta C_f$

It will be seen later in section 3.3 that the readings (yielded by the TLD readers) of the TLD cards is in the unit of nC. For the TLD cards to give the readings in mSv, these cards must have a calibration coefficient C_f (mSv/nC). This section describes the method on how to get this C_f, together with its uncertainty ΔC_f.

Cs-137 (662 keV) source was used for this purpose and all the six cards were placed in front of the water phantom at a 2 meters source-to-detector distance. The exposure-rate of this source at this distance and on the day of the experiment is a computer-calculated value $\dot{K}_{Cs\text{-}137}$ (mGy/min). Knowing the conversion coefficient $\frac{Hp(10)}{K_{air}}$ (Sv/Gy) for the 662 keV (and also for the other ten energies) [5] and the exposure time t, we may get the calibrated $H_p(10)$, i.e. $H_p(10)_{cal}$ from the formula of

$$H_p(10)_{cal} = \dot{K} \times t \times \frac{Hp(10)}{K_{air}} \quad (4)$$

In this work we chose t=5 minutes. After this calibration process, the charge of the TLD card q is obtained from the TLD reader. The uncertainty in q, Δq is taken as 0.03q [10]. From these two values $H_p(10)_{cal}$ and q, $C_f \pm \Delta C_f$ for each card was calculated from:

$$C_f \pm \Delta C_f = \frac{H_p(10)_{cal}}{q} \pm H_p(10)_{cal} \times \left(\frac{\Delta q}{q^2}\right) \quad (5)$$

2.2 Determination of delivered $H_p(10)$, $H_p(10)_{del} \pm \Delta H_p(10)_{del}$

Equation (1) gives R = $H_p(10)_{meas}/H_p(10)_{del}$. As to check the accuracy, R should be around 1. To do this, the delivered dose $H_p(10)_{del}$ must first be fixed, then the measured dose by the TLD card $H_p(10)_{meas}$ is compared with the $H_p(10)_{del}$.

In this work, $H_p(10)_{del}$ from the eleven radiation sources were fixed to 1 mSv. To get this 1 mSv, the irradiation time t needs to be determined. Substituting $H_p(10)_{cal}$ with $H_p(10)_{del}$= 1mSv and re-arranging the formula in equation (4), we now have

$$t = \frac{1\ mSv}{\dot{K} \times \frac{Hp(10)}{K_{air}}} \quad (6)$$

The $\dot{K}$ (mGy/min), obtained at 2 m detector-to-source distance, was (a) by the use of ion chamber for the lower photon energies, (b) by the use of the computer-calculated table for the 662 and 1250 keV. The product in the denominator of equation (6) i.e. $\dot{K}$(mGy/min)× $\frac{H\mathrm{p}(10)}{\mathrm{K}_{air}}$ (Sv/Gy) is $\dot{H}_\mathrm{p}(10)$ (mSv/min), therefore we now have

$$t \pm \Delta t = \frac{1\ \mathrm{mSv}}{\dot{H}\mathrm{p}(10)\ \mathrm{mSv/min}} \pm t \times \frac{\Delta\dot{H}_\mathrm{p}(10)}{\dot{H}_\mathrm{p}(10)} \quad (7)$$

It is obvious that t has the unit of minutes. This calculated t should be re-checked that $\dot{H}_p(10) \times t = \mathrm{H_p(10)_{del}} = 1$ mSv is obtained. The uncertainty is calculated by

$$\mathrm{H_p(10)_{del}} \pm \Delta\mathrm{H_p(10)_{del}} = \dot{H}_\mathrm{p}(10) \times \mathrm{t} \pm H_\mathrm{p}(10)_\mathrm{del} \times \left[\left(\frac{\Delta\dot{H}_\mathrm{p}(10)}{\dot{H}_\mathrm{p}(10)}\right)^2 + \left(\frac{\Delta\mathrm{t}}{\mathrm{t}}\right)^2\right]^{\frac{1}{2}} \quad (8)$$

After this irradiation time t is obtained, irradiation of the four TLD cards i.e TLD signal cards is done. During the irradiation, each TLD card was put inside TLD holder and placed in front of the water phantom at 2 meters source-to-detector distance. After the irradiation, TLD signal cards need to be stored for 24 hours to stabilize the electron trapping process. The other two cards i.e. TLD control cards were not be irradiated and used as background reading.

2.3 Determination of Measured $H_p(10)$, $H_p(10)_{meas} \pm \Delta H_p(10)_{meas}$

The routine readout procedure using the Harshaw Model 4500 hot-gas reader was used to get the reading of four TLD signal charge, $q_s \pm \Delta q_s$ in the unit of nC. As mention in the section 3.1, this charge value need to be multiplied with C_f to get the $H_\mathrm{p}(10)_\mathrm{meas}$ in the unit of mSv.

It will be seen later in this section (in equation (12)) that $H_\mathrm{p}(10)_\mathrm{meas} = \overline{H_\mathrm{p}(10)_{g\ meas}} - \overline{H_\mathrm{p}(10)_{b\ meas}}$ where $\overline{H_\mathrm{p}(10)_{g\ meas}}$ is the gross dose (obtained as the average of the four TLD cards) and $\overline{H_\mathrm{p}(10)_{b\ meas}}$ is the background dose (obtained as the average of the two TLD cards).

$$H_\mathrm{p}(10)_\mathrm{g\ meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{g\ meas} = \mathrm{q_s} \times \mathrm{C_f} \pm H_\mathrm{p}(10)_{g\ meas} \times \left[\left(\frac{\Delta q_s}{q_s}\right)^2 + \left(\frac{\Delta \mathrm{C}_f}{\mathrm{C}_f}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

Taking the average readout of four TLD signal cards,

$$\overline{H_\mathrm{p}(10)_{g\ meas}} \pm \Delta\overline{H_\mathrm{p}(10)_{g\ meas}} = \frac{\sum_{i=1}^{4} H_p(10)_{g\ meas}}{4} \pm \frac{\left[\sum_{i=1}^{4} (\Delta H_p(10)_{g\ meas})^2\right]^{\frac{1}{2}}}{4} \quad (10)$$

Two TLD control cards that have not been irradiated were used to get the TLD background charge. This is important to get the true reading of TLD signal cards. The reading of TLD control cards need to be carried out at the same time with the reading of TLD signal cards. Using the same method to get dose of $\overline{\mathrm{H_p}(10)_{g\ meas}}$, the average of TLD background dose can be calculated from

$$\overline{H_\mathrm{p}(10)_{b\ meas}} \pm \Delta\overline{H_\mathrm{p}(10)_{b\ meas}} = \frac{\sum_{i=1}^{2} H_p(10)_{b\ meas}}{2} \pm \frac{\left[\sum_{i=1}^{2} (\Delta H_p(10)_{b\ meas})^2\right]^{\frac{1}{2}}}{2} \quad (11)$$

Using the two values of $\overline{H_\mathrm{p}(10)_{g\ meas}}$ and $\overline{H_\mathrm{p}(10)_{b\ meas}}$, the net $H_\mathrm{p}(10)$ measured can be calculated

$$H_\mathrm{p}(10)_\mathrm{meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{meas} = \overline{H_\mathrm{p}(10)_{g\ meas}} - \overline{H_\mathrm{p}(10)_{b\ meas}} \pm \left[\Delta\overline{H_\mathrm{p}(10)_{\mathrm{g}\ meas}}^2 + \Delta\overline{H_\mathrm{p}(10)_{b\ meas}}^2\right]^{\frac{1}{2}} \quad (12)$$

2.4 Determination of $H_p(10)_{meas}/H_p(10)_{del}$ ratio, R±ΔR

From equations (7) and (11), $H_\mathrm{p}(10)_\mathrm{meas}/H_\mathrm{p}(10)_\mathrm{del}$ ratio can be calculated

$$R \pm \Delta R = \frac{H_\mathrm{p}(10)_{meas}}{H_\mathrm{p}(10)_{del}} \pm R \times \left[\left(\frac{\Delta H_\mathrm{p}(10)_{meas}}{H_\mathrm{p}(10)_{meas}}\right)^2 + \left(\frac{\Delta H_\mathrm{p}(10)_{del}}{H_\mathrm{p}(10)_{del}}\right)^2\right]^{\frac{1}{2}} \quad (13)$$

Table 2 An example of $H_\mathrm{p}(10)_\mathrm{meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{meas}$ determination. In this case data for energy 24 keV is taken

Step	Quantity determined	Eqn	Card No.	Value ± Uncertainty	(Uncertainty/Value)×100 %
1	$C_f \pm \Delta C_f$(mSv/nC)	5	8252(1	0.0022 ± 0.0001	4.55
			8253(1	0.0023 ± 0.0001	4.35
			8254(1	0.0023 ± 0.0001	4.35
			8256(1	0.0022 ± 0.0001	4.55
			8245(2	0.0023 ± 0.0001	4.35
			8246(2	0.0021 ± 0.0001	4.76
2	$H_\mathrm{p}(10)_\mathrm{del} \pm \Delta H_\mathrm{p}(10)_\mathrm{del}$ (mSv)	8	-	1.00 ± 0.019	1.90
3.1	$q \pm \Delta q$ (nC)	-	8252	483.4 ± 14.50	3.00
			8253	469.2 ± 14.08	3.00
			8254	475.7 ± 14.27	3.00
			8256	488.3 ± 14.65	3.00
			8245	3.883 ± 0.12	3.00
			8246	4.308 ± 0.13	3.00
3.2	$H_\mathrm{p}(10)_\mathrm{g\ meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{g\ meas}$ (mSv)	10	8252	1.06 ± 0.05	4.24
			8253	1.06 ± 0.04	4.24
			8254	1.08 ± 0.05	4.24
			8256	1.08 ± 0.05	4.24
			Average	1.07 ± 0.02	2.12
3.3	$H_\mathrm{p}(10)_\mathrm{b\ meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{b\ meas}$ (mSv)	11	8245	0.01 ± 0.0004	4.00
			8246	0.01 ± 0.0004	4.00
			Average	0.01 ± 0.0004	4.00
3.4	$H_\mathrm{p}(10)_\mathrm{meas} \pm \Delta H_\mathrm{p}(10)_\mathrm{meas}$ (mSv)	12	-	1.06 ± 0.02	2.14
4	$R \pm \Delta R$	13	-	1.06 ± 0.03	2.86

[a] TLD signal card; [b] TLD control card

3.0 RESULTS AND DISCUSSION

Table 2 shows the results of $R \pm \Delta R$ obtained in stages (for energy 24 keV as an example) in accordance with the calculations steps described in Section 3. It can be seen that for steps 1 to 3 (before step 4 where R is obtained), the uncertainty order is from 1.90% to 4.76%. The uncertainty however is reduced to 2.86% (for R in step 4). This is because, the uncertainties that are responsible to provide ΔR (in step 4) are small, i.e. 1.90% in step 2 and 2.14% in step 3.4.

The calculation in Table 2, could be repeated to get $R \pm \Delta R$ for the other 10 energies. Results of $R \pm \Delta R$ for all energies are shown in Table 3. It can be seen from this table that ΔR is in the range of ±0.02 to ±0.04, or the percentage uncertainty from 2.15–2.86%. These results are also presented in Figure 2. In comparison with the work done by Luo & Rotunda in 2006 [11] which also used the TLD-100H, the present results showed a good degree of agreement.

Table 3 The R ± ΔR values for eleven energies studied

Ref. radiation	Energy (keV)	R ± ΔR	(ΔR/R)×100%
N-30	24	1.06 ± 0.03	2.86
N-40	32	1.16 ± 0.04	3.20
N-60	47	1.06 ± 0.03	3.27
N-80	65	0.93 ± 0.03	3.30
N-100	84	0.82 ± 0.03	3.30
N-120	102	0.79 ± 0.03	3.46
N-150	121	0.77 ± 0.03	3.28
N-200	171	0.81 ± 0.03	3.31
N-250	218	0.85 ± 0.03	3.32
S Cs-137	662	1.00 ± 0.02	2.15
S Co-60	1250	1.04 ± 0.02	2.19

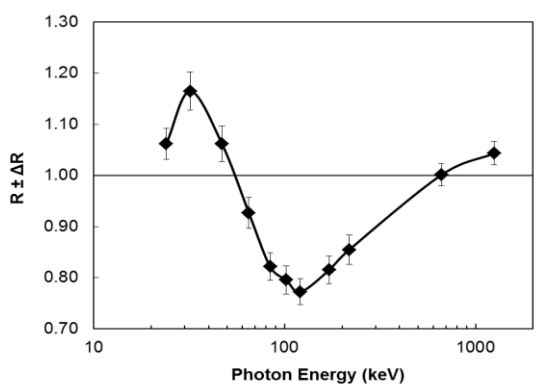


Figure 2 R±ΔR values of TLD-100H at energy 24-1250 keV

To see the compliance of this $R \pm \Delta R$ with the ICRP's lower and higher limits, a trumpet graph (R versus $H_p(10)_{del}$) is plotted as shown in Figure 3. It can be seen that all $R \pm \Delta R$ are within the limits. This also means that there are no cases where the R value lies outside the limit. Based on these results, it can be concluded that the experimental value of $H_p(10)_{meas}$ are satisfactory.

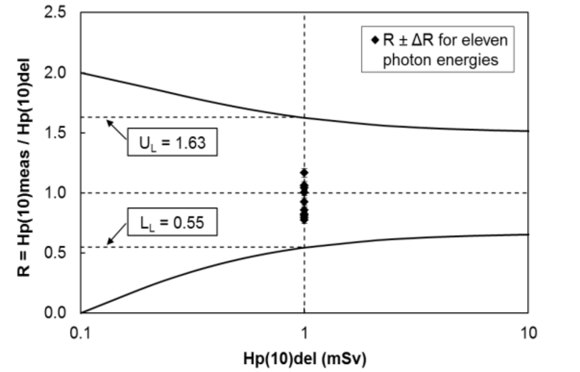


Figure 3 The graphical representation of equations (1)-(3) and the location of R±ΔR

4.0 CONCLUSION

The method to estimate the uncertainty in $H_p(10)_{meas}/H_p(10)_{del}$ ratio, R has been described and determined for TLD-100H. It is for the purpose of considering the value of R, whether to accept or to reject, when R is slightly higher or lower that the ICRP trumpet graph acceptance limit. Despite no such cases arise in this work (as $R \pm \Delta R$ all are well within the trumpet graph limit), the method described here might be useful for boundary cases, i.e. when R is near the limits.

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