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Determination of $\overline{W}_{air}$ (mean energy expended in air per ion pair formed) from absorbed dose standard comparison at BIPM

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Introduction

The comparisons of absorbed dose standards recently carried out at BIPM can be considered from two different points of view. The first one consists in assuming that the values of $\overline{W}_{air}$ and $\overline{\overline{f}}$ (mean stopping power ratio of air to carbon) are known and comparing the values of the absorbed dose rates $\dot{D}_{nat.lab.}$ and $\dot{D}_{BIPM}$ measured in the ^{60}Co BIPM beam by the calorimeter of the national laboratory concerned and by the BIPM ionization chamber. Such results were given at the last meeting of Section I (May 1977) [1] .

The alternative way of treating the experimental data of these comparisons supposes that the accuracy is sufficiently good to derive from measurements values of $\overline{W}/\overline{\overline{f}}$ which are competitive with the current values. This is the object of the present paper. After giving $\overline{W}/\overline{\overline{f}}$, we have chosen to deduce $\overline{W}$*, using provisionally the values of mean excitation energies of Berger and Seltzer [2] for the calculation of $\overline{\overline{f}}$.

Determination of $\overline{W}/\overline{\overline{f}}$

The values of $\overline{W}/\overline{\overline{f}}$ are obtained from

$$\frac{\overline{W}}{e\,\overline{\overline{f}}} = \dot{D}_{nat.lab.} \left(\frac{v\,\rho_a}{I\,\Pi K_i}\right)_{BIPM} , \qquad (1)$$

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* For the sake of simplicity, we write $\overline{W}$ instead of $\overline{W}_{air}$. This symbol means, in the present paper, the mean energy expended in dry air per ion pair formed.

where

$\overline{W}$ is the mean energy expended in dry air per ion pair formed,

e is the electronic charge,

$\overline{\overline{f}}$ is the mean ratio of the mass stopping power of air to that of carbon which can be calculated as explained in the next paragraph,

$\dot{D}_{nat.lab.}$ is the absorbed dose rate measured in the ^{60}Co BIPM beam at a depth Z inside a graphite phantom, with the calorimetric standard of the national laboratory concerned,

$\left(\frac{I \Pi K_i}{v \rho_a}\right)_{BIPM}$ is the corrected mass ionization current measured in the same beam at the same depth in the phantom*, with the BIPM ionometric standard. It includes

I, the ionization current,

v, the volume of the cavity in which the charge is collected,

ρ_a, the air density under the measurement conditions.

$\Pi K_i = K_l K_s K_h K_p K_i$, the product of correction factors due to the following causes:

K_l = leakage current,

K_s = loss of ionization due to recombination,

K_h = presence of water vapor in the air,

K_p = perturbation due to the presence of the cavity inside the graphite phantom,

K_i = reference to a phantom of infinite diameter.

K_h is taken equal to 0.997 [1], the same as K_h for a cavity chamber placed in air because K_h is not very dependent on the photon energy (see for instance in [3,4] the small difference between K_h for ^{60}Co and K_h for ^{137}Cs).

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* In the NBS-BIPM comparison, the depths were slightly different (0.009 g cm^{-2}) for the two standards, the correction for this difference was 0.02 to 0.04% according to the depth. Note that the front part of the phantom (before the calorimeter or the ionization chamber) was made of the same graphite disks to get rid of eventual systematic errors.

K_p is calculated according to [5,6] . This correction is applied only to the front and back wall contribution which is multiplied by exp $(-\mu' u)$ F , where

μ' is the linear attenuation coefficient of graphite for the photons incident upon the phantom*,

u is the thickness of the half cavity,

F is a factor which takes into account the variation with Z of the fluence of the incident photons and of the photons scattered by the phantom material and the variation with u of the energy dissipated by the electrons liberated by these photons.

K_p varies from 0.995 1 to 0.985 6 when $\rho_c Z$ increases from 1 to 17 g cm^{-2} (ρ_c is the graphite density).

K_i is calculated as k_p by means of a Monte-Carlo method. Due to the large diameter of the BIPM phantom ($\emptyset \approx$ 30 cm), K_i corresponds to a small correction (K_i = 1.000 1 to 1.000 4).

Table 1 (col. 2 and 6) gives for $\rho_c Z$ from 1 to 17 g cm^{-2} the values of $\overline{W}/e\,\overline{\overline{f}}$ obtained from Eq. (1) for NBS-BIPM and LMRI-BIPM comparisons. For a same depth, the values obtained in the two comparisons differ at most by 0.4%. This difference is not significant at a 95% confidence level.

Determination of $\overline{W}$

At present, the uncertainties of the current values of $\overline{W}$ and $\overline{\overline{f}}$ are of the same order of magnitude ($\approx$ 0.5%) and one can wonder what is more advisable to deduce from $\overline{W}/\overline{\overline{f}}$: either $\overline{W}$ (assuming $\overline{\overline{f}}$ known) or $\overline{\overline{f}}$ (assuming $\overline{W}$ known**). In this paper, we have chosen the first alternative because

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* The incident radiation includes an important part of scattered radiation produced in the source itself and in the surrounding materials. This scattered radiation and its spectral distribution were calculated using a Monte-Carlo method. On the whole, the energy fluence of this incident scattered radiation amounts to 19% of that of the primary radiation.

** To avoid a vicious circle, $\overline{W}$ should be known by measurements using β sources and large chambers in which the energy of the electrons is entirely dissipated so that the $\overline{W}$ values obtained are not dependent on some $\overline{f}$ value.

Table 1 – Values of $\overline{W}/e$ deduced from absorbed dose standard comparisons at BIPM

Depth D nominal values ($g\ cm^{-2}$) (1)	NBS-BIPM comparison $\overline{W}/e\bar{\bar{f}}$ (J/C)	$\bar{\bar{f}}$ (2)	$\overline{W}/e$ (J/C)	Standard deviation v (%) (3)	LMRI-BIPM comparison $\overline{W}/e\bar{\bar{f}}$ (J/C)	$\bar{\bar{f}}$ (2)	$\overline{W}/e$ (J/C)	Standard deviation v (%) (3)
1	34.030	0.990 6	33.710	0.11				
3	33.982	0.990 2	33.649	0.11	33.96	$0.990\ 1_5$	33.63	0.20
5	34.043	0.989 9	33.699	0.10	34.01	0.989 9	33.67	0.16
6					34.03	0.989 8	33.68	0.20
7	34.045	0.989 7	33.695	0.10	34.09	0.989 7	33.74	0.19
8					34.02_5	$0.989\ 6_5$	33.67	0.23
10	34.130	0.989 6	33.775	0.10	34.01	$0.989\ 5_5$	33.66	0.25
12	34.160	0.989 5	33.802	0.10	34.03	$0.989\ 4_5$	33.67	0.21
15	34.175	0.989 4	33.812	0.10	34.18	$0.989\ 3_5$	33.81	0.27
17					33.97_5	0.989 3	33.61	0.28

(1) The depths are slightly different ($0.15\ g\ cm^{-2}$) in the two comparisons.

(2) The mean stopping-power ratios $\bar{\bar{f}}$ are calculated with the I values from Berger and Seltzer [1] .

(3) The relative standard deviations v are taken equal to $\left[(s_{\dot{D}}/\dot{D})^2 + \mathcal{E}_s^2\right]^{1/2}$, where $s_{\dot{D}}$ is the standard deviation of the calorimetric measurements and $\mathcal{E}_s$ an estimated value (0.1%) for the error coming from the lack of reproducibility due to the rotation of the BIPM source-holder disk.

an ICRU committee is now reviewing the $\overline{W}$ values and preparing a report on this subject. It seems interesting to take advantage of the good quality of international comparison measurements to produce a value of $\overline{W}$ for dry air which is reliable enough to be included in the ICRU Report on $\overline{W}$.

The values of $\overline{\overline{f}}$ given here are calculated using the values of mean excitation energies of Berger and Seltzer, namely I_{air} = 86.8 eV and I_c = 78.0 eV. $\overline{\overline{f}}$ is calculated from the Spencer-Attix theory as $\overline{f}$ in [7], but an additional integration is necessary to take into account the energy distribution $\psi_{h\nu}$ of the energy fluence of photons since the primary photons are accompanied with the incident scattered photons (see above) and with the photons scattered inside the phantom.

The columns 3 and 7 of Table 1 give $\overline{\overline{f}}$ at the different depths used in the comparisons. From $\overline{W}/e\overline{\overline{f}}$ and $\overline{\overline{f}}$, the values of $\overline{W}/e$ are obtained (col. 4 and 8 in Table 1). Table 2 shows the weighted mean values of $\overline{W}/e$ for each comparison. Since these two values do not differ significantly (at 95% confidence level), a general weighted mean has been calculated which is 33.70 $J \cdot C^{-1}$, a value close to the value 33.73 $J \cdot C^{-1}$ recommended by ICRU in 1964 [8]. However, this agreement is somewhat fortuitous because the $\overline{W}$ values entering into the mean value 33.73 eV were obtained from measurements generally carried out in humid air. No correction or a wrong correction was made for the presence of water vapor. Besides, for the authors using a cavity chamber, the $\overline{f}$ value was based on I values which are different from those of Berger and Seltzer.

Table 3 shows the components of the systematic uncertainty in the present $\overline{W}$ determination. When added quadratically, they give a total equal to about 0.6%. Of course, the most important component is the uncertainty concerning $\overline{\overline{f}}$ (0.5%).

Table 2 - Mean values of $\overline{W}/e$ deduced from comparisons performed at BIPM

Mean calculated from the results of:	$\overline{(\overline{W}/e)}$ (J/C) (1)	Standard deviation (%) (2)	Degrees of freedom	Systematic uncertainty (%) (3)
- NBS-BIPM comparison (Table 1, col. 2)	33.74	0.069	6	
- LMRI-BIPM comparison (Table 1, col. 6)	33.68	0.051	8	0.65
- both comparisons (Table 1, col. 2 and 6 as a whole)	33.72	0.046	15	

(1) $\overline{(\overline{W}/e)}$ is a weighted mean where the weights w_i are taken equal to $1/v_i^2$, with the v_i from column 5 or 9 of Table 1.

$$m = \overline{(\overline{W}/e)} = \sum_{i=1}^{k} w_i\,(\overline{W}/e)_i \Big/ \sum_{i=1}^{k} w_i\,,$$ with k = 7, 9 or 16, according to the case.

(2) The standard deviation $s_m = \left[\sum w_i \left[(\overline{W}/e)_i - m\right]^2 \Big/ (k-1) \sum w_i\right]^{1/2}$.

Here are given the relative standard deviations s_m/m.

(3) See details in Table 3.

Table 3 - Systematic uncertainties (%) entering in the determination of $\overline{W}/e$

1. Physical data	ρ_{STP}		0.01
	$\overline{\overline{f}}$		0.5
2. Calorimetric measurement		0.11 to 0.12 (NBS)	0.22 (LMRI)
3. Ionometric measurement $I/v\rho$	v		0.1
	I		0.02
	corrections concerning ρ — pressure		0.01
	corrections concerning ρ — temperature		0.01
4. Correction factors (ionometric measurement)	K_h		0.1
	K_s		0.01
	K_p		0.3
	K_i		0.02 to 0.04
5. Comparison conditions	depth and graphite density		0.1
	source distance		0.02
Square root of quadratic sum		0.62 (NBS)	0.65 (LMRI)

Conclusion

These first two comparisons lead to a $\overline{W}$ value for dry air which seems to be quite reliable if the values of the mean excitation energies are correct. It will be interesting to see if the future comparisons (in particular the forthcoming PTB-BIPM comparison) confirm the present result.

Another ICRU committee is presently working on the subject of stopping powers and discussing the best values of I to be recommended by ICRU. When the work of this committee is completed, a new set of $\overline{\overline{f}}$ values will have to be calculated and the values of $\overline{W}/e$ in Table 1 should be revised accordingly.

Even if the I values are not yet well known, it is possible to deduce from the $\overline{W}/e\,\overline{\overline{f}}$ values given above a reliable value for $\overline{W}/e\,\overline{f}$, where $\overline{f}$ is the mean stopping power ratio of air to carbon to be used for the BIPM graphite cavity chamber placed in air. This quantity can be calculated with an uncertainty ($\approx$ 0.3%) smaller than the present uncertainties of $\overline{W}$ and $\overline{f}$ ($\approx$ 0.5% for each). This is particularly interesting if Section I decides to adopt standards of air kerma. The accuracy of such standards would be greater than the accuracy of the present exposure standards.

References

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