Rapport BIPM-79/2

The conversion factors C_E and C_λ revisited

M.-T. Niatel

Institut National de la Santé et de la Recherche Médicale, Paris

This tentative document is intended to clarify the basic relations which allow one to deduce the absorbed dose in water from the measurements obtained with an ionization chamber calibrated in terms of exposure in free air. The analysis is based on work done at the Bureau International des Poids et Mesures (BIPM) concerning the determination of exposure (Allisy 1967, Boutillon and Niatel 1973) and the determination of absorbed dose (Boutillon and Niatel 1979). We suppose that the walls of the ionization chamber are made of a single water-equivalent material and that their thickness is sufficient to ensure electronic equilibrium for the radiation used in the exposure calibration.

The relevant energy ranges are those considered in Reports 14 and 21 (ICRU 1969, 1972). Table 1 gives the symbols and definitions of the main quantities used. Table 2 shows schematically the various steps leading to the absorbed dose conversion factors C_E and C_λ .

Table 1

List of symbols

D_w Absorbed dose at the reference point in the undisturbed water phantom (in the absence of the ionization chamber).

$\dot{E}_a/m$ Mass energy imparted to the air in the cavity. It is the quotient of E_a by m, where E_a is the energy imparted by ionizing radiation to the air filling the chamber cavity and m the mass of the air in this cavity.

$(E_a/m)_o$ Mass energy imparted to the air in an ideal cavity. It is the limit of E_a/m when the real cavity, supposed to be walled by the phantom material, tends to an ideal Bragg-Gray cavity which does not disturb the electron fluence in the phantom. The position of this ideal cavity is assumed to be at the center of the real cavity.

J_a Mass ionization charge. It is the quotient of the ionization charge by the mass of air in the cavity (it is assumed that J_a is corrected for leakage charge, water vapor in air and loss of ionization due to recombination).

K_a Air kerma at the reference point in the undisturbed water phantom.

K_w Water kerma at the reference point in the undisturbed water phantom.

M Exposure meter reading corrected for temperature, pressure, humidity, leakage and lack of saturation voltage.

N Exposure calibration factor given by a standardizing laboratory for ^{60}Co gamma rays.

P_{wa} Perturbation correction which should be applied to the mass energy E_a/m imparted to the air in the cavity to obtain the mass energy $(E_a/m)_o$ imparted to the air in an ideal cavity. The subscript wa recalls that the perturbation is due to the insertion of an air cavity in a water phantom. The symbols $(p_{wa})_\lambda$ and $(p_{wa})_E$ refer to photon and electron beams, respectively.

X_a Exposure in free air at the reference point, in the absence of the ionization chamber.

X_w Exposure at the reference point in the undisturbed water phantom.

α Sensitivity of the exposure meter defined by the relation $\alpha = J_a/M$.

For J_a, M and N the following subscripts are used:

ch refers to the cavity chamber calibrated in terms of exposure in free air and used subsequently to obtain the absorbed dose in water,

c refers to the calibration conditions,

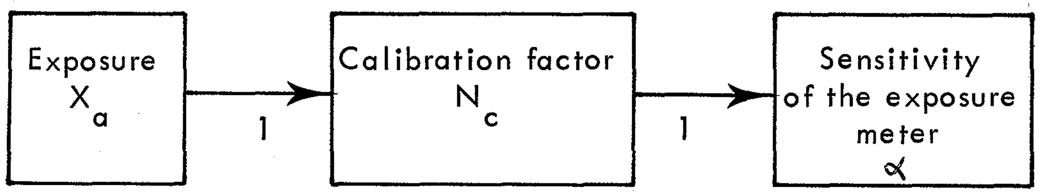
u refers to the user's conditions.

Table 2

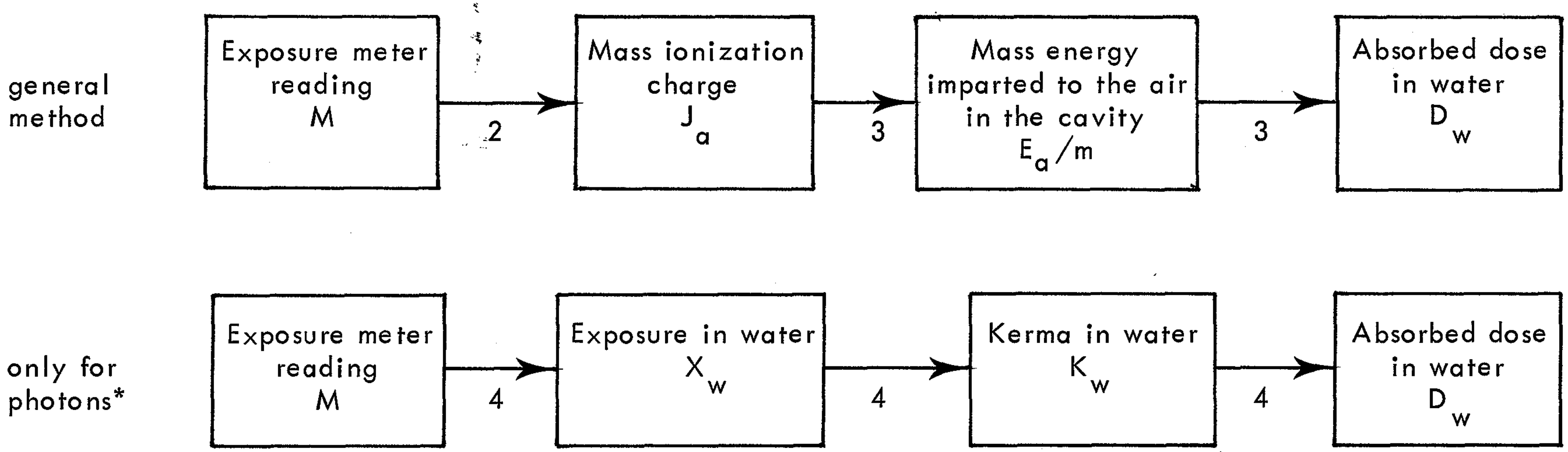
Diagram showing the relations involved in the derivation of C_E and C_λ

(The numbers under the arrows refer to the corresponding sections in the text)

a) Calibration in free air



b) Determination of the absorbed dose in water



* with energies close to the energy of the calibration radiation

1. The exposure calibration factor N and parameters involved

The exposure in free air at the reference point P is supposed to be determined in a ^{60}Co gamma-ray beam with the exposure standard S of the national standard laboratory. Let $(X_a)_s$ be the value obtained. The chamber CH to be calibrated is placed, with its center at P, in the same beam as S and the reading obtained after correction is called $M_{ch,c}$. The exposure calibration factor $N_{ch,c}$ of chamber CH is defined as

$$N_{ch,c} = \frac{(X_a)_s}{M_{ch,c}} . \qquad (1)$$

Because of the use which is normally made of the factor $N_{ch,c}$, a more explicit knowledge of the parameters entering it is needed. Let us first assume that chamber CH is a primary chamber, which requires that the correction factors for the determination of exposure are known. The value of the exposure in free air as measured by chamber CH should be

$$(X_a)_{ch} = (J_a)_{ch,c} \left[\frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_w}\right]_c (\bar{\bar{s}}_{wa})_c (\prod_i K_i)_{ch,c} , \qquad (2)$$

where $(J_a)_{ch,c}$ is the mass ionization charge collected in chamber CH under calibration, corrected as indicated in Table 1,

μ_{en}/ρ is the mass energy absorption coefficient, with subscripts a for air and w for water (or water equivalent wall material)*; subscript c refers to the calibration radiation,

$\bar{\bar{s}}_{wa}$ is the mean ratio of the restricted mass stopping power of the wall material to that of air for the electrons crossing the cavity, with the same meaning as above for subscript c,

$(\prod_i K_i)_{ch,c}$ is the product of the chamber correction factors under calibration conditions (Boutillon and Niatel 1973, Niatel et al. 1975); thus more explicitly

$$(\prod_i K_i)_{ch,c} = K_{st} K_{rn} K_{an} K_{wall} ,$$

where

K_{st} corrects for scattering of the chamber stem,

K_{rn} for radial non-uniformity of the beam,

---

* If the scattered radiation in the incident beam is sufficiently low, the ratio of the μ_{en}/ρ's can be taken equal to the mean of the ratios for the 1.17 and 1.33 MeV photons.

K_{an} for axial non-uniformity of the beam,

K_{wall} is the product of the corrections concerning the chamber walls (for the BIPM flat chambers we have $K_{wall} = K_{at}\, K_{CEP}\, K_{sc}$, which includes wall attenuation K_{at}, a reduction K_{CEP} of this attenuation due to the position of the mean center of electron production and wall scattering K_{sc}).

From (1) we get $(X_a)_s = M_{ch,c}\, N_{ch,c}$, which is equal to $(X_a)_{ch}$ given by (2), and since the mass ionization $(J_a)_{ch,c}$ can be assumed to be proportional to the exposure meter reading $M_{ch,c}$, i.e. $(J_a)_{ch,c} = \alpha M_{ch,c}$, we have

$$N_{ch,c} = \alpha \left[\frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_w}\right]_c (\bar{\bar{s}}_{wa})_c \left(\prod_i K_i\right)_{ch,c} . \qquad (3)$$

2. Remarks concerning the use of the exposure calibration factor

Before giving explicit expressions for the absorbed dose conversion factors C_E and C_λ, it may be worth considering a frequent application of $N_{ch,c}$. To measure the absorbed dose in water in the user's beam (the nature of the radiation concerned has not to be specified at the moment), the calibrated chamber CH is placed in a water phantom and the reading $M_{ch,u}$ is obtained. In many cases (e.g. for electrons, high-energy photons), the calibration factor $N_{ch,c}$ is in fact used only to derive from (3) the sensitivity α of the instrument. Hence the mass ionization charge which is defined as

$$(J_a)_{ch,u} = \alpha\, M_{ch,u}$$

is actually calculated by

$$(J_a)_{ch,u} = M_{ch,u}\, N_{ch,c} \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c \frac{1}{(\bar{\bar{s}}_{wa})_c \left(\prod_i K_i\right)_{ch,c}} . \qquad (4)$$

This is a rather laborious method for merely obtaining the mass ionization charge. Measurement of the cavity volume v together with an electrical calibration of the exposure meter, giving r in terms of coulombs per division, would seem a more straightforward way. The required sensitivity α (in terms of C kg^{-1} per division) is simply equal to $r/v\rho$, where ρ is the air density at the time of the electrical calibration. Thus we do not need the quantity $\left(\prod_i K_i\right)_{ch,c}$ which depends on the chamber and also on the calibration conditions (source-chamber distance, for instance). In fact, the evaluation of $\left(\prod_i K_i\right)_{ch,c}$ is generally made in a rather approximate way by using a traditional numerical value (0.985) for many different circumstances. Besides, if the nature of the wall material is not clearly indicated, it may happen that the factors $\left[(\mu_{en}/\rho)_w / (\mu_{en}/\rho)_a\right]_c$ and $1/(\bar{\bar{s}}_{wa})_c$ are omitted, thus assuming implicitly that the walls are air equivalent, as pointed out by Nahum and Greening (1977) and some other authors.

3. Derivation of C_E and C_λ

The absorbed dose in water D_w can be obtained by assuming that the chamber CH can be regarded as a Bragg-Gray cavity (see paragraph 2.2.2 in ICRU 1969 and paragraph 6.2.3 in ICRU 1972). Since the real cavity is of finite size, a perturbation correction p_{wa} (defined in Table 1)* has to be applied to the mass energy E_a/m imparted to the air in the cavity. For an ideal cavity we have

$$(E_a/m)_o = (E_a/m)\, p_{wa} = (J_a)_{ch,u}\, (W/e)\, p_{wa} \,, \tag{5}$$

where W is the mean energy expended in air per ion pair formed and e is the electronic charge. The other symbols are explained in Table 1.

By application of the Bragg-Gray principle, we obtain for the absorbed dose in water

$$D_w = (E_a/m)_o\, (\bar{\bar{s}}_{wa})_u = (J_a)_{ch,u}\, (W/e)\, (\bar{\bar{s}}_{wa})_u\, p_{wa} \,. \tag{6}$$

From (4) and (6) we have

$$D_w = M_{ch,u}\, N_{ch,c} \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c} \frac{p_{wa}}{(\prod_i K_i)_{ch,c}} \frac{W}{e} \,. \tag{7}$$

According to the current definitions of the absorbed dose conversion factors for photons and electrons C_λ and C_E, we have

$$D_w = M_{ch,u}\, N_{ch,c}\, C_\lambda \,, \tag{8}$$

$$D_w = M_{ch,u}\, N_{ch,c}\, C_E \,. \tag{9}$$

---

* In fact, an additional correction must be added for the displacement of water by the chamber stem. For the sake of simplicity, however, it is omitted in the following equations.

For water equivalent wall material we can write

$$C_\lambda = \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c} \frac{(p_{wa})_\lambda}{(\overline{\prod_i} K_i)_{ch,c}} \frac{W}{e} , \tag{10*}$$

$$C_E = \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c} \frac{(p_{wa})_E}{(\overline{\prod_i} K_i)_{ch,c}} \frac{W}{e} . \tag{11**}$$

Actually, the C_E values given in paragraph 6.2.3 of Report 21 (ICRU 1972) are calculated by assuming implicitly that the walls are air equivalent. In this case the expression for C_E reduces to

$$C_E = (\bar{\bar{s}}_{wa})_u \frac{(p'_{wa})_E}{(\overline{\prod_i} K'_i)_{ch,c}} \frac{W}{e} . \tag{11 bis***}$$

This form of C_E is equivalent to the one given in ICRU 1972 (footnote 4, p. 43) as

$$C_E = A \; s_{w,g} \; p_{w,g} \; \overline{W}/e ,$$

where A replaces $(\overline{\prod_i} K'_i)^{-1}_{ch,c}$. However, the ICRU factor A does not include all correction factors K_i needed for exposure determination, but only the wall attenuation factor.

---

* The symbol $\bar{\bar{s}}_{wa}$ (as in Appendix A in ICRU 1969) is used here since there is a continuous energy distribution of photons inside the phantom.

** Note that from the definitions of $(E_a/m)_o$ and p_{wa} given in Table 1, $(p_{wa})_E$ includes the correction currently called perturbation correction (Harder 1968) as well as another one which is closely related to the usual displacement correction (Dutreix and Dutreix 1966, Hettinger et al. 1967).

*** The symbol $(\overline{\prod_i} K'_i)_{ch,c}$ is used here instead of $(\overline{\prod_i} K_i)_{ch,c}$ since the material of the chamber wall is different. Likewise $(p'_{wa})_E$ replaces $(p_{wa})_E$ because the perturbation correction includes an additional factor to account for the insertion of the air-equivalent wall in the water phantom.

4. Alternative derivation of C_λ (only for photon energies close to the energy of the calibration radiation)

In paragraph 2.2.1 of Report 14 (ICRU 1969) another method is used for evaluating C_λ which is quite different from the one given above. It is only applicable to a photon energy range for which the concept of exposure is valid from an experimental point of view.

In this method it is assumed that the exposure X_w in the undisturbed water phantom can be obtained from the reading $M_{ch,u}$ of the chamber placed in the phantom with its center at the reference point. The relation is written as

$$X_w = M_{ch,u} N_{ch,c} d , \tag{12}$$

where d is a rather complex factor which will be studied in more detail in Section 5.

The exposure X_w is related to the air kerma K_a in the undisturbed water phantom by the relation

$$X_w = K_a (1 - g_a) e/W , \tag{13}$$

where g_a is the fraction of electron energy which is lost to bremstrahlung in air.

The air kerma K_a and the water kerma K_w are respectively proportional to the values of the mass energy-transfer coefficients $(\overline{\mu_{tr}/\rho})_a$ and $(\overline{\mu_{tr}/\rho})_w$ averaged for the photon energy fluence spectrum in the phantom. Equation (13) can be written in the form

$$X_w = K_w \left[\frac{(\overline{\mu_{tr}/\rho})_a (1 - g_a)}{(\overline{\mu_{tr}/\rho})_w} \right]_u \frac{e}{W} , \tag{14}$$

which corresponds to

$$K_w = X_w \left[\frac{(\overline{\mu_{tr}/\rho})_w}{(\overline{\mu_{en}/\rho})_a} \right]_u \frac{W}{e} . \tag{15}$$

Finally, the absorbed dose in water, $D_w = b K_w$ is expressed by

$$D_w = b X_w \left[\frac{(\overline{\mu_{tr}/\rho})_w}{(\overline{\mu_{en}/\rho})_a} \right]_u \frac{W}{e} = M_{ch,u} N_{ch,c} b d \left[\frac{(\overline{\mu_{tr}/\rho})_w}{(\overline{\mu_{en}/\rho})_a} \right]_u \frac{W}{e} , \tag{16}$$

from which C_λ is obtained as

$$C_\lambda = b\, d \left[\frac{(\overline{\mu_{tr}/\rho})_w}{(\overline{\mu_{en}/\rho})_a} \right]_u \frac{W}{e} \; . \qquad (17)$$

At first sight, this expression (equation 2.8 in ICRU 1969) seems to be different from (10). However, it is possible to show that they are equivalent (see section 6).

5. Analysis of the parameters entering into the factor d

It is not a straightforward matter to write explicitly the relation between the mass ionization charge $J_{ch,u}$ measured in the water phantom and the exposure in water X_w. We have tried to do it in the derivation below which is based on the BIPM analysis (Boutillon and Niatel 1979). It supposes that the chamber involved is a flat chamber of the BIPM type.

Let us first remind some basic relations given in Boutillon (1979) for determining the absorbed dose in water D_w from ionometric measurements. For this purpose we write the Bragg-Gray relation as

$$D_w = (E_a/m)\,(p_{wa})_\lambda\,(\bar{\bar{\bar{s}}}_{wa})_u \; . \qquad (18)$$

The perturbation correction $(p_{wa})_\lambda = (E_a/m)_o \big/ (E_a/m)$ is obtained by means of the following two equations which express $(E_a/m)_o$ and (E_a/m) in terms of the kerma in water K_{wp} of the primary radiation (incident on the phantom) at the reference point

$$(E_a/m)_o = K_{wp}\, F_o \big/ (\bar{\bar{\bar{s}}}_{wa})_u \, , \qquad (19)$$

$$E_a/m = K_{wp}\, e^{\mu' u}\, F \big/ (\bar{\bar{\bar{s}}}_{wa})_u \, . \qquad (20)$$

The expressions for F_o and F can be found in Boutillon (1979). They include terms taking into account the influence on the energy dissipated by electrons, of the variation with depth in the phantom of the primary radiation fluence and of the scattered radiation fluence. The factor $e^{\mu' u}$ corrects for the absence of primary radiation attenuation in the cavity, where μ' is the linear attenuation coefficient of the wall material for the primary radiation and u is the thickness of each half cavity.

From (19) and (20) we have

$$(p_{wa})_\lambda = e^{-\mu' u}\, F_o / F \; . \qquad (21)$$

We shall now relate X_w to $(J_a)_{ch,u}$ by means of (15) and (20). With Boutillon (1979) we call R the ratio of the kerma in water of the scattered radiation K_{ws} and of the primary radiation K_{wp} at the reference point in the phantom, i.e.

$$R = K_{ws}/K_{wp} \; . \qquad (22)$$

Since $K_w = K_{wp} + K_{ws}$, (20) may be written as

$$E_a/m = (J_a)_{ch,u}\,(W/e) = K_w\, e^{\mu' u}\, F \big/ (1+R)\,(\bar{\bar{s}}_{wa})_u \; . \qquad (23)$$

Substituting (23) into (15) yields

$$(J_a)_{ch,u} = X_w \left[\frac{(\overline{\mu_{tr}/\rho})_w}{(\overline{\mu_{en}/\rho})_a}\right]_u \frac{e^{\mu' u}\, F}{(1+R)\,(\bar{\bar{s}}_{wa})_u} \; . \qquad (24)$$

By taking into account (4) we finally obtain

$$X_w = M_{ch,u}\, N_{ch,c} \left[\frac{(\overline{\mu_{en}/\rho})_w}{(\overline{\mu_{en}/\rho})_a}\right]_c \left[\frac{(\overline{\mu_{en}/\rho})_a}{(\overline{\mu_{tr}/\rho})_w}\right]_u \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c}\; \frac{(1+R)\, e^{-\mu' u}}{F(\overline{\prod_i} K_i)_{ch,c}} \; . \qquad (25)$$

By comparing (25) with (12) we find

$$d = \left[\frac{(\overline{\mu_{en}/\rho})_w}{(\overline{\mu_{en}/\rho})_a}\right]_c \left[\frac{(\overline{\mu_{en}/\rho})_a}{(\overline{\mu_{tr}/\rho})_w}\right]_u \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c}\; \frac{(1+R)\, e^{-\mu' u}}{F(\overline{\prod_i} K_i)_{ch,c}} \; . \qquad (26)$$

This expression is much more complicated than those currently used for evaluating d. In fact, it seems that there has been often some confusion between d and A. Furthermore, in the literature the symbol A has several meanings, namely

a) $$A = (K_{wall})^{-1}_{ch,c} \; , \qquad (27)$$

as in ICRU (1972), where only the so-called wall attenuation factor is taken into account;

b) $$A = \left[\frac{(\overline{\mu_{en}/\rho})_w}{(\overline{\mu_{en}/\rho})_a}\right]_c (\bar{\bar{s}}_{wa})^{-1}_c\, (K_{wall})^{-1}_{ch,c} \; , \qquad (28)$$

(NACP 1978), in which the lack of air equivalence of the wall material is corrected for, but the K_i's different from K_{wall} are ignored;

c) the complete expression (Henry 1979)

$$A = \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c (\bar{\bar{s}}_{wa})_c^{-1} (\prod_i K_i)_{ch,c}^{-1} \quad . \tag{29}$$

The Appendix gives numerical values of d and of different A's for the BIPM chamber when the quantity concerned is the absorbed dose in graphite.

6. Comparison of the two expressions of C_λ

Two different expressions for C_λ have been given above as (10) and (17) which result from the methods of derivation given in sections 3 and 4.

It is possible to compare these expressions by means of (26). We must also calculate b which should be introduced in (17), i.e.

$$b = \frac{D_w}{K_w} = \frac{D_w}{K_{wp}(1+R)} \quad . \tag{30}$$

From (6) and (19) we obtain

$$D_w = (E_a/m)_o (\bar{\bar{s}}_{wa})_u = K_{wp} F_o \ , \tag{31}$$

which gives

$$b = F_o/(1+R).$$

Substituting now b and d into (17), we obtain after simplification

$$C_\lambda = \frac{F_o}{F} e^{-\mu' u} \left[\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}\right]_c \frac{(\bar{\bar{s}}_{wa})_u}{(\bar{\bar{s}}_{wa})_c} \frac{1}{(\prod_i K_i)_{ch,c}} \frac{W}{e} \quad . \tag{33}$$

Since $F_o e^{-\mu' u}/F$ is the perturbation correction $(p_{wa})_\lambda$ given by (21), we conclude that (33) is in fact identical to (10).

Conclusion

We recall that the purpose of this paper is limited to presenting some of our reflections on the difficult problem of determining absorbed dose in water, not to give any definite solution. Even under the simplifying assumption of a perfect water equivalence for the chamber walls, a rigorous determination of C_E and C_λ is not a straightforward matter because of the many parameters entering into these factors. The situation is still more complicated for the chambers presently available since they often consist of a mixture of materials. Further experimental work on these subjects, as carried out for instance by Henry (1979), is highly desirable.

It should be noted that whereas the direct measurement of the sensitivity α (section 2) could shorten somewhat the way to obtain D_w, the determination of the stopping-power ratio $(\bar{\bar{s}}_{wa})_u$ and of the perturbation correction p_{wa} corresponding to the real experimental conditions remains a difficult problem. Further theoretical and experimental studies are needed to improve the present situation.

Appendix

To give an idea of the numerical difference between d and A, let us consider the case of the absorbed dose in graphite (instead of the absorbed dose in water for which we have not yet made the calculations). The following values concern the BIPM graphite cavity chamber which is cylindrical (pill-box type) and has the following dimensions:

diameter	outside	5.05 cm
	inside	4.50 cm
height	outside	1.07 cm
	inside	0.52 cm
collecting plate	diameter	4.10 cm
	thickness	0.11 cm
collecting volume		6.787 cm^3
front wall thickness		0.273 cm, i.e. 0.506 g cm^{-2}.

The calibration conditions are:

- ^{60}Co gamma rays,
- source-chamber distance 1.12 m
- beam diameter at reference plane ≈ 10 cm.

The conditions for measurements of absorbed dose in graphite are:

source-chamber distance		1 m
beam size (at the middle of penumbra)		10 cm x 10 cm
measurement depth		2.81 cm, i.e. 5.018 g cm^{-2}
graphite phantom	diameter	29.7 cm
	thickness	18.8 cm

contribution of scattered radiation in the incident beam (in terms of energy fluence) ≈ 18%.

Further details can be found in Boutillon and Niatel (1973) and Boutillon (1979).

The factors entering in (26) which gives d (for graphite instead of water) are

$$\left[(\mu_{en}/\rho)_{ca}/(\mu_{en}/\rho)_a\right]_c = 1.001\,5 \text{ (values taken from Hubbell 1977)},$$

where the subscript ca refers to carbon.

$\left[\overline{(\mu_{en}/\rho)}_a \big/ \overline{(\mu_{tr}/\rho)}_{ca}\right]_u = 0.998,$

$(\bar{\bar{s}}_{ca,a})_u \big/ (\bar{\bar{s}}_{ca,a})_c = 1.010\,2/1.007\,8 = 1.002\,4^*,$

$1 + R = 1.270\,3,$

$e^{-\mu' u}/F = (p_{wa})_\lambda / F_o = 0.988\,9/1.274 = 0.776,$

$(\overline{\Pi}\, K_i)^{-1}_{ch,c} = 0.998\,3\,.$

Then d (for graphite) = 0.986. Let us compare d to the different values of A (eq. 27 to 29) calculated for the BIPM graphite cavity chamber:

$$A = (K_{wall})^{-1}_{ch,c} = 0.996\,4\,,$$

$$A = \left[(\mu_{en}/\rho)_{ca} \big/ (\mu_{en}/\rho)_a\right]_c (\bar{\bar{s}}_{ca,c})^{-1}_c\, (K_{wall})^{-1}_{ch,c} = 0.990\,2\,,$$

$$A = \left[(\mu_{en}/\rho)_{ca} \big/ (\mu_{en}/\rho)_a\right]_c (\bar{\bar{s}}_{ca,a})^{-1}_c\, (\overline{\Pi}\, K_i)^{-1}_{ch,c} = 0.992\,1.$$

We can give also two other numerical values:

a) b (from eq. 30) for the same measurement depth (≈ 5 g cm^{-2}) in graphite, is equal to 1.003,

b) $(C_\lambda)_{ca}$ (from eq. 10 or 33) in the same conditions, using the value W/e = 33.85 eV given in ICRU (1979).

$$(C_\lambda)_{ca} = 0.866 \text{ rad} \cdot R^{-1} \text{ or } 33.55 \text{ Gy/C} \cdot \text{kg}^{-1}\,.$$

---

* The mean ratios of the restricted stopping powers of carbon and air are calculated according to Berger and Seltzer (1964) with their values for the mean excitation energies (I_{ca} = 78.0 eV, I_a = 86.8 eV).

References

Allisy, A.: Metrologia 3, 41 (1967) and Recueil de Travaux du Bureau International des Poids et Mesures (BIPM) 1, (1966-1967)

Berger, M.J., Seltzer, S.M.: in Studies in Penetration of Charged Particles in Matter (Fano, U., Ed.) (US Nat. Acad. Sci.-Nat. Research Council Pub. 1133, Washington, DC, 1964), p. 205

Boutillon, M., Niatel, M.-T.: Metrologia 9, 139 (1973) and Recueil de Travaux du BIPM 4 (1973-1974)

Boutillon, M.: Rapport BIPM-79/6 (1979)

Dutreix, J., Dutreix, A.: Biophysik 3, 249 (1966)

Harder, D.: Biophysik 5, 157 (1968)

Henry, W.H.: Phys. Med. Biol. 24, 37 (1979)

Hettinger, G., Petterson, C., Svensson, H.: Acta Radiologica 6, 61 (1967)

Hubbell, J.H.: Radiat. Res. 70, 58 (1977)

ICRU (International Commission on Radiation Units and Measurements), Radiation Dosimetry: X rays and gamma rays with maximum photon energies between 0.6 and 50 MeV, Report 14 (ICRU Publications, Washington, DC) (1969)

ICRU, Radiation Dosimetry: Electrons with initial energies between 1 and 50 MeV, Report 21 (ICRU Publications, Washington, DC) (1972)

ICRU, Average energy required to produce an ion pair, Report 31 (ICRU Publications, Washington, DC) (1979)

Nahum, A.E., Greening, J.R.: Phys. Med. Biol. 22, 1020 (1977)

Niatel, M.T., Loftus, T.P., Oetzmann, W.: Metrologia 11, 17 (1975) and Recueil de Travaux du BIPM 4 (1973-1974)

NACP, Recommendations by the Nordic Association of Clinical Physics, preprint (1978)

(March 1979)