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IONIZATION CHAMBER DOSIMETRY FOR PHOTON AND ELECTRON BEAMS

Theoretical considerations

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The theoretical aspects of the use of calibrated ionization chambers to determine the dose in phantom for electrons and photons above 1 MeV are discussed in the present report. From these theoretical considerations differences in experimental methods will be detailed and experimental data will be given to confirm theoretical conclusions.

It is not a new subject and it has been extensively discussed in the literature (TUBIANA & DUTREIX 1958, WHYTE 1959, BARNARD 1964, GREENE & MASSEY 1966, ALMOND 1967, SVENSSON & PETTERSSON 1967, among others) but still considerable confusion exists in the correct use of calibrated ionization chambers and in the assumptions made when deriving the basic formula. MATSUZAWA et coll. (1974) suggested that perhaps the C_E-values published by ICRU (1972) for use in calibrating high energy electrons may be incorrect by as much as 3 per cent. The basis for this view was the assumption that the ionization chamber wall with build-up cap was considered perspex equivalent at the time of calibration in a standard ^{60}Co or 2 MV roentgen beam. GREENING (1974) replied that commercial thimble ionization chambers act as if the wall of the chamber is air equivalent in which case the published values of C_E are correct.

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By effective-wall material is meant that material surrounding the air volume from which the secondary electrons crossing the cavity appear to originate. The expression given by MATSUZAWA et coll. for correcting from air equivalence to perspex has been derived many times and is well known (WHYTE 1959, BARNARD 1964, JOHNS & CUNNINGAM 1969, among others). It has also been predicted previously that most electrons would come from the material immediately surrounding the air volume and was first shown experimentally by GRAY (1937). Therefore, the conclusion reached by GREENING that, 'in practice the use of a lucite build-up cap with ^{60}Co radiation does not seriously impair the air-equivalence of an ionization chamber which was designed for equivalence', appears reasonable. However, when the C_λ values for roentgen radiation are considered almost all theoretical derivations are based upon the opposite conclusion, i.e. that with the build-up on the chamber acts as non air-equivalent. In fact, the assumption is generally made that the chamber acts as water-equivalent. Since these two assumptions (i.e. at the time of chamber calibration with build-up cap the chamber acts either as air equivalent or water equivalent) are mutually exclusive and since the differences will amount to 3 per cent or more in the dose calibration, a detailed analysis of this subject seems to be warranted.

Calibration at ^{60}Co gamma beam

Relation between exposure and cavity ionization. The first step in the ionization chamber dosimetry is to determine the response of the chamber for charge of one sign per unit mass of air inside the air cavity, J_{air}. This quantity could be determined directly for a chamber of known volume and thus known mass of air if the chamber is connected to a calibrated charge measuring instrument. However, the volume is usually not known and furthermore these measurements are too complicated for an ordinary radiation therapy center. A simpler procedure is to make use of the exposure calibration for ^{60}Co gamma rays of the ionization chamber for the evaluation of J_{air}. ^{60}Co is designated the calibration quality in the following and given the index c.

The exposure measurements at standard laboratories are carried out through determination of $J_{air,c}$ for graphite chambers (NIATEL et coll. 1975). The $J_{air,c}$ value is then corrected for wall attenuation, differences in mass energy absorption coefficients and stopping powers between air and graphite etc. in order to obtain the exposure. In the use of an exposure calibrated ionization chamber, the opposite direction, i.e. from exposure to J_{air}, is necessary. The simplest case should be to use an ionization chamber similar to the one at the standard laboratory as the relation between exposure and J_{air} in this case is known. Chambers used in practice differ from such a case. However, the inner chamber wall is very often of graphite or of a material very near air-equivalent. In the derivation, a two-component cylindrical ionization chamber is considered, a wall (wl), which is often designed to be air-equivalent and a build-up cap (b), which is designed to be either air or water-equivalent. However, in the derivations there is no restriction as to the material of the wall or the build-up cap. The exposure at a point P in air is known at the calibration laboratory. An ionization chamber is placed with its center at P. The total chamber thickness (wl + b) is adjusted so as to just establish maximum electron build-up at its center. If the exposure at P is X_{air} then the calibration factor N_c of the ionization chamber with measuring assembly is given by

$$X_{air,c} = M_c N_c \tag{1}$$

where M_c is the instrument reading. (Minor corrections introduced due to radiation-induced leakage, recombination losses etc. are not considered.) The cavity ionization with air-equivalent walls is given by

$$J_{air,c} = M_c N_c A_{eq} \tag{2}$$

where A_{eq} is a factor less than unity, introduced due to the attenuation of the radiation. It is considered that electrons which give ionization in the cavity are generated 'up-stream' (BURLIN 1968) and that, therefore, A_{eq} should not include the attenuation from all the layer, wl + b. A_{eq} is approximated with 0.985 for cylindrical ionization chambers of ordinary size (SVENSSON & PETTERSSON 1967, JOHNS & CUNNINGHAM 1969). For an ionization chamber with the wall and build-up of the same material m, $J_{air,c}$ is given by (WHYTE 1959, LOFTUS & WEAVER 1974):

$$J_{air,c} = M_c N_c A_{eq} \left(\frac{\mu_{en}}{\varrho}\right)_{air}^{m} \cdot \left(\frac{S}{\varrho}\right)_{m}^{air} \tag{3}$$

For the two-component chamber where a fraction α of the ionization is due to electrons appearing to be generated in the build-up material ($m_1 = b$) and a fraction 1-α from the wall itself ($m_2 = wl$), equation 3 may be approximated by

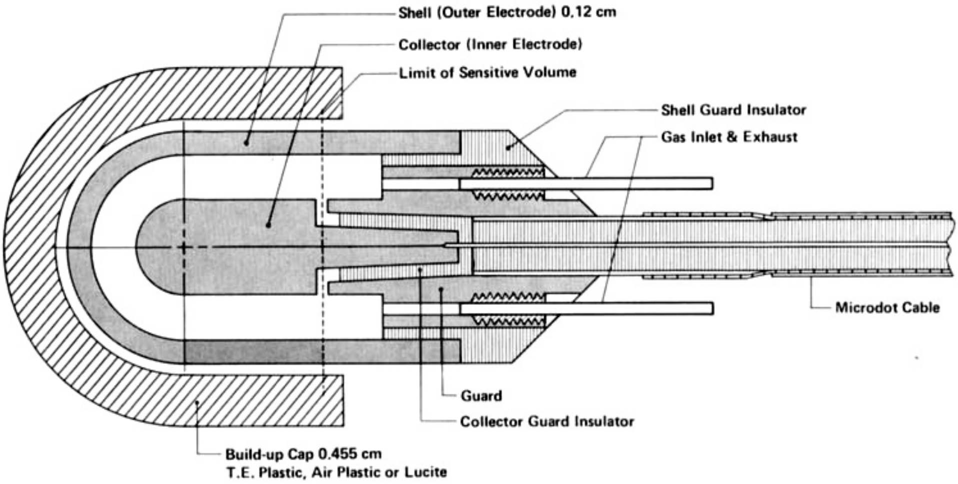
$$J_{air,c} = M_c N_c A_{eq} \left[\alpha \left(\frac{\mu_{en}}{\varrho}\right)_{air}^{b} \left(\frac{S}{\varrho}\right)_{b}^{air} + (1-\alpha) \left(\frac{\mu_{en}}{\varrho}\right)_{air}^{wl} \left(\frac{S}{\varrho}\right)_{wl}^{air}\right] \tag{4a}$$

or

$$J_{air,c} = M_c N_c A_{eq} A_m \tag{4b}$$

The derivation of A_m is over-simplified since the electron elastic scattering between different layers is not considered. This effect could be of significance for a compound chamber, a fact that is supported from recent TLD measurements with similar geometrics (BERTILSSON 1975, RUDÉN 1975). Therefore, experiments are more convenient for the determination of A_m.

Experimental determination of A_m. Experiments have independently been carried out by the two authors to estimate the value of the factor A_m for cylindrical chambers of a size and construction often used for dose measurements in photon or electron beams.



Spokus Chambers used to investigate the factor A_m as a function of wall material and build-up cap material. In addition to T.E. plastic. Air plastic and Lucite (perspex) a build-up cap of aluminium was also used. ▒ T.E. Plastic (A-150) or air-equivalent (C-552), □ copper, ▥ polyethylene.

Svensson used a cylindrical chamber with a diameter of 6 mm and length 20 mm. The wall thickness was 0.1 g cm^{-2} graphite. The central electrode had a diameter of 1 mm and was also made of graphite. Caps of graphite, perspex, and aluminium were placed over the wall and were adjusted in thickness to give maximum response for ^{60}Co radiation. The responses were normalized to the uniform graphite chamber. Almond did a different set of measurements using two ionization chambers also with wall thicknesses of approximately 0.1 g cm^{-2}; one constructed of air equivalent plastic, the other of tissue equivalent plastic (Figure). Four different caps were used (Table). All caps were made the same size, 4 mm in wall thickness so that when they are used on the chamber in a water phantom the amount of water displaced will be the same. Because their linear attenuation coefficients varied, it was necessary to measure and correct for the different attenuations of the caps in the broad beam geometry used for the experiments. The responses were normalized to the uniform air equivalent plastic chamber.

The experimental A_m-values were compared with the two sets of values derived from the equation (4 a) using the extreme assumptions, i.e. $\alpha = 0$, where all electrons giving ionization in the cavity appear to come from the chamber wall, and $\alpha = 1$, where all electrons appear to come from the build-up cap. All the experiments gave a better agreement with $\alpha = 0$ than $\alpha = 1$ (Table). Also for a build-up cap of aluminium, which has a higher atomic number than the wall, the response is very close to that for the condition $\alpha = 0$. The differences could be attributed to electron scattering and not included in the calculation. To investigate the needed decrease of the graphite wall thickness to meet the requirement in ICRU Report No. 14 that $\alpha = 1$ a separate

Table

The theoretical A_m-values were calculated from equation 4 a. $(\mu en/\varrho)^{m}_{air}$ and $(s/\varrho)^{air}_{m}$ were taken from ICRU Report 10 b. Tissue equivalent plastic (T. eq.) was assumed to be muscle for these calculations

Material		Theoretical A_m		Experimental A_m	
b (cap)	wl (wall)	$\alpha=0$	$\alpha=1$	SVENSSON	ALMOND
air eq.*	air eq.	1.00	1.00	1.000*	1.000*
perspex	air eq.	1.00	0.97	0.994	0.992
water	air eq.	1.00	0.98		
aluminium	air eq.	1.00	1.09	1.002	0.982
T. eq.	air eq.	1.00	0.97		0.988
T. eq.	T. eq.	0.97	0.97		0.972**
air eq.	T. eq.	0.97	1.00		0.969
perspex	T. eq.	0.97	0.97		0.973
aluminium	T. eq.	0.97	1.09		0.965

* Graphite or air-equivalent plastic.
** Normalization point.

set of measurements were performed according to the method given by SVENSSON. A chamber with the same dimensions as the one described but with a very thin inner wall of graphite ≈ 0.03 g cm^{-2} was constructed. The outer wall and cap was graphite or perspex. These measurements gave $A_m = 0.985$ with the perspex cap, i.e. a value between that for $\alpha=0$ and $\alpha=1$. Thus, even a thinner electrode layer has to be used to follow ICRU No. 14. Therefore, it seems simpler to make chambers that meet the condition $\alpha=0$ than $\alpha=1$ particularly the inner electrode is made of an air-equivalent layer (e.g. graphite).

It could be concluded that the wall material is of larger significance for A_m than the build-up material at least with wl ≥ 0.1 cm^{-2}, and that the effective-wall (page 178) material therefore in most cases is the material of the inner chamber wall.

Dose measurements at a photon beam quality λ

Theory. The $J_{air,c}$ calibrated chamber is to be used for dose measurements at a photon beam quality λ. It is assumed that the measurements are made with the thimble ionization chamber without build-up cap in a water phantom and that a fraction β of the ionization comes from electrons generated in the water and a fraction 1-β from electrons generated in the wall.

The absorbed dose to the water may then be approximated by

$$D_{water,\lambda} = I_\lambda \frac{W}{e} \left[\beta \left(\frac{S}{\varrho}\right)^{water}_{air} + (1-\beta) \left(\frac{S}{\varrho}\right)^{wl}_{air} \left(\frac{\mu_{en}}{\varrho}\right)^{water}_{wl} \right]_\lambda dp \qquad (5)$$

The cases for $\beta=0$ and $\beta=1$ have been discussed previously (JOHNS & CUNNINGHAM 1969, ICRU No. 14). A review of the methods for the evaluation of the stopping power ratios are given in the ICRU Report No. 14. The factor p is introduced to correct for the distorsion in electron fluence caused by the differences in electron multiple scattering in the probe and air cavity compared with that of the phantom material. The factor d corrects for reduction of attenuation when the air cavity replaces phantom material.

It is assumed that the calibration in charge of one sign per unit mass of air and scale division at quality c, i.e. ^{60}Co γ is also valid at other qualities λ provided appropriate corrections are made for recombination losses, stem leakage etc. If the chamber is irradiated so that the same reading is obtained at quality λ as for the ^{60}Co γ case then $I_c=I_\lambda$ and I_c can be substituted from equation (4 b) into (5).

$$D_{water,\lambda} = M_\lambda \cdot N_c \cdot A_{eq} \cdot A_m \cdot \frac{W}{e}\left[\beta\left(\frac{S}{\varrho}\right)_{air}^{water} + (1-\beta)\left(\frac{S}{\varrho}\right)_{air}^{wl}\left(\frac{\mu_{en}}{\varrho}\right)_{wl}^{water}\right] dp \qquad (6)$$

All roentgen protocols take $\beta=1$, $p=1$, $d=1$, and for the A_m determination $\alpha=1$ and $b=$ water. Applying these assumptions on equation (4 a) and (6) give

$$D_{water,\lambda} = M_\lambda \cdot N_c \cdot A_{eq} \frac{W}{e}\left[\frac{\left(\frac{\mu_{en}}{\varrho}\right)_{air}^{water}}{\left(\frac{S}{\varrho}\right)_{air}^{water}}\right]_c \left(\frac{S}{\varrho}\right)_{air,\lambda}^{water} \qquad (7)$$

where

$$C_{water,\lambda} = A_{eq} \cdot \frac{W}{e}\left[\frac{\left(\frac{\mu_{en}}{\varrho}\right)_{air}^{water}}{\left(\frac{S}{\varrho}\right)_{air}^{water}}\right]_c \left(\frac{S}{\varrho}\right)_{air,\lambda}^{water} \qquad (8)$$

and thus

$$D_{water,\lambda} = M_\lambda \cdot N_c \cdot C_{water,\lambda} \qquad (9)$$

$C_{water,\lambda}$ is named C_λ in the ICRU Report No. 14. A_{eq} has been taken as 0.985 in all the protocols.

For photons at a very high energy with a thin wall ionization chamber, it may be reasonable to take $\beta=1$ but the α-value ought to be lower than 1. It should be a better approximation to use $\alpha=0$ for these chambers according to the experiment related in the Table. Therefore, if the inner wall is made of an air-equivalent material then equation (8) should be

$$C_{air,\lambda} = A_{eq} \cdot \frac{W}{e}\left[\frac{\left(\frac{\mu_{en}}{\varrho}\right)_{air}^{air,eq}}{\left(\frac{S}{\varrho}\right)_{air}^{air,eq}}\right]_c \cdot \left[\frac{S}{\varrho}\right]_{air,\lambda}^{water} \qquad (10)$$

and thus

$$D_{water,\lambda} = M_{\lambda} N_c C_{air,\lambda} \qquad (11)$$

The first bracket in epuation (10) should thus be 1 for a complete air-equivalent material. For carbon used as an air-equivalent material this factor should formally be 1.005 for a chamber calibrated at NBS as that factor is used in the calculation of exposure from cavity ionization in graphite.

$C_{air,\lambda}$ is approximately 3 per cent, plus 0.5 per cent if graphite is taken as air-equivalent wall material, higher than $C_{water,\lambda}$ according to the Table and the foregoing discussion. Experiments were made by ALMOND to confirm this difference.

Experimental. The tissue ($\approx$water) and air-equivalent chamber described were calibrated in air for ^{60}Co radiation. Build-up caps in the same materials as the chamber walls were used. Appropriate differences in attenuation for the build-up caps were corrected for as the same linear thicknesses of the two caps were used in spite of different electron densities. The displacement and pertuberation corrections were not considered as the two air cavities had identical shape and size.

Measurements were then carried out in the water phantom at 25 MV roentgen radiation, now with the caps removed. The two chambers were irradiated in identical geometrics to the same doses. The two sets of measurements made it possible to determine directly $C_{air,\lambda}/C_{water,\lambda}$, which was 1.034, which is in agreement with the theory. The question is often raised whether the ^{60}Co build-up cap should be left on at another energy when the chamber is in a water phantom. Repeated experiments at higher energies (25 MV photons) have indicated no measurable difference with the cap on or off when the cap is of perspex. However, since the cap is usually assumed to be water-equivalent it seems advisable to leave it off whenever possible.

Dose measurements at electron radiation, quality E

Theory. For the air-equivalent walled chamber, the assumptions given in ICRU Report No. 21 are made and

$$D_{water,E} = I_E \frac{W}{e} \left(\frac{S}{\varrho}\right)^{water}_{air,\bar{E}} dp \qquad (12)$$

where $(s/\varrho)^{water}_{air,\bar{E}}$ is the mass collision stopping power ratio calculated at the mean energy of the primary electrons at the point of measurement. For this case of air-equivalent wall material A_m is equal to 1.00 in equation (4 b). The equations (4 b) and (12) will then give, if $I_E = I_{air,c}$

$$D_{water,E} = M_E \cdot N_c \cdot \frac{W}{e} \cdot A_{eq} \left(\frac{S}{\varrho}\right)^{water}_{air,\bar{E}} dp \qquad (13)$$

$$D_{water,E} = M_E N_c C_{air,\bar{E}} \qquad (14)$$

where

$$C_{air,E} = A_{eq}\frac{W}{e}\left(\frac{S}{\varrho}\right)_{air,\bar{E}}^{water} dp \tag{15}$$

All $C_{air,E}$ (named C_E in ICRU No. 21) factors have been calculated using this equation. For the case of tissue-equivalent or water-equivalent walled chambers and assuming that $\beta = 1$ again equation 12 would become

$$D_{water,E} = I_E\frac{W}{e}\left(\frac{S}{\varrho}\right)_{air,\Delta}^{water} dp \tag{16}$$

where Δ has generally been taken as 0.1 MeV (ICRU No. 21) which results in a $C_{water,E}$ of

$$C_{water,E} = A_{eq}\frac{W}{e}\left[\frac{\left(\frac{\mu_{en}}{\varrho}\right)_{air}^{water}}{\left(\frac{S}{\varrho}\right)_{air}^{water}}\right]_c \left(\frac{S}{\varrho}\right)_{air,\Delta}^{water} \tag{17}$$

The ratio of the unrestricted to restricted stopping power ratios with a cutoff of 0.1 MeV for these low Z material at these energies 7 to 20 MeV is probably very close to unity (BURLIN 1968). The ratio $C_{air,E}/C_{water,E}$ was investigated by ALMOND.

Experimental. The experiments were made in the same way as for the $C_{air,\lambda}/C_{water,\lambda}$ ratios. The mean energies at the point of measurements were 7, 13, and 18 MeV. The ratios $C_{air,E}/C_{water,E}$ were determined to be 1.027, 1.015 and 1.019, respectively, as compared to a calculated value of ≈ 1.03. The agreement is thus consistent with the theory.

Because these experiments were done with special ionization chambers, it was decided to look for this effect with commercial ionization chambers also. (Since these experiments were carried out the chambers used have become commercially available from the Exradin Corporation.) Two chambers were used, an EG & G 0.1 cm^3 tissue equivalent ionization chamber and a Farmer 0.6 cm^3 graphite chamber. The chamber responses were measured in a ^{60}Co beam using the appropriate build-up caps of tissue equivalent plastic ($\approx$ water) and perspex, respectively. The measured ratio ($\approx C_{air,E}/C_{water,E}$) for 13 MeV electrons was 1.036 which agrees well with the expected theoretical one.

No appreciable difference could be detected using the chambers in a water phantom with or without the normal perspex build-up caps, i.e. variations of less than ± 0.2 per cent were found.

Conclusions

For high energy photons, when ionization chambers that are designed to be air-equivalent at ^{60}Co new C_λ-values ($C_{air,\lambda}$) must be used. These are approximately 3 per cent higher than the published C_λ factors ($C_{water,\lambda}$). The C_λ at lower energies will differ less from formerly published values. Experiments for the transition region also including the ^{60}Co quality will be reported later.

For tissue equivalent chambers the published values of C_λ ($C_{water,\lambda}$) can be used.

For electrons the published C_E ($C_{air,E}$) values can be used as long as the chamber is air-equivalent. For tissue-equivalent chambers, new C_E-values must be used. These are 3 per cent lower than the C_E ($C_{water,E}$) values.

For both electrons and photons, it is recommended that the cap will be taken off when the chamber is used in a water phantom, since the cap is taken to be water-equivalent in any case. However, experimentally little difference in the chamber reading is seen with or without the cap.

The displacement and pertuberation factors have not been discussed in this report. More experimental values are today available, sometimes differing from the data, given by ICRU. In order to simplify the procedure for the hospital physicists C_λ and C_E values for typical ionization chambers ought to be given including these corrections and also taking into consideration the different wall materials. (Such data will later be discussed and are also under preparation by working-groups by the Nordic Association of Clinical Physics (NACP) and American Association of Physicist in Medicine (AAPM).)

Finally, there has always appeared to be a discrepancy between the G-values of $FeSO_4$ for electrons and photons if the G-values are evaluated from ionization chamber measurements using the concepts of C_E and C_λ (Law & Naylor 1972). The change in $C_{water,\lambda}$ to $C_{air,\lambda}$ would result in a reduction of the G-value for photons by approximately 3 per cent which would bring the G-values for photons and electrons into very close agreement.

SUMMARY

New C_λ-values ($C_{air,\lambda}$) are proposed which should be applied for ionization chambers with an inner wall of air-equivalent material, air eq. plastic or graphite. The new values are up to approximately 3 per cent higher than those published in the ICRU Report No. 14 and here named $C_{water,\lambda}$ as the inner wall is considered water-equivalent. Also two sets of C_E-values are proposed, namely $C_{air,E}$ which is given in ICRU No. 21 and $C_{water,E}$ which is approximately 3 per cent lower, and apply for a chamber with an inner wall lining of water-equivalent material.

ZUSAMMENFASSUNG

Neue C_λ-Werte ($C_{Luft,\lambda}$) werden vorgeschlagen, welche bei Ionisationskammern mit einer inneren Wand von Luft-äquivalentem Material, Luft-äquivalentem Plast oder Graphit, angewendet werden sollten. Die neuen Werte sind bis zu etwa 3 Prozent höher als die in ICRU Raport Nr. 14 publizierten Werte und werden hier $C_{Wasser,\lambda}$ benannt, da die innere Wand als Wasser-äquivalent angenommen wird. Zwei Arten von C_E-Werten werden auch vorgeschlagen, nämlich $C_{Luft,E}$, welcher in ICRU Nr. 21 gegeben ist, und $C_{Wasser,E}$, welcher etwa 3 Prozent niedriger ist und für Kammern mit einer inneren Wand, die von Wasser-äquivalentem Material ausgekleidet ist, verwendet wird.

RÉSUMÉ

Des nouvelles valeurs de C_λ ($C_{air,\lambda}$) sont proposées; elles devraient être utilisées pour les chambres d'ionisation ayant une paroi interne faite d'un matériau équivalent à l'air; plastique ou graphite équivalent à l'air. Ces nouvelles valeurs sont jusqu'à environ 3% supérieures à celles publiées dans le rapport ICRU n° 14 et qui sont nommées ici $C_{eau,\lambda}$ étant donné que la paroi interne est considérée comme équivalente à l'eau. Les auteurs proposent aussi deux séries de valeurs C_E; à savoir $C_{air,E}$ qui sont celles données dans le rapport ICRU n° 21 et $C_{eau,E}$ qui est approximativement inférieure de 3% et s'applique à une chambre dont la paroi interne est faite d'un matériau équivalent à l'eau.

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