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FROM THE DEPARTMENT OF RADIATION PHYSICS, SAHLGRENSKA SJUKHUSET, GÖTEBORG, THE RADIATION PHYSICS DEPARTMENT, UNIVERSITY OF UMEÅ, UMEÅ, SWEDEN, AND THE CENTER FOR RADIATION RESEARCH, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, GAITHERSBURG, MD, USA.

ABSORBED DOSE IN WATER

Comparison of several methods using a liquid ionization chamber

O. Mattsson, H. Svensson, G. Wickman, S. R. Domen, J. S. Pruitt and R. Loevinger

Abstract

In the present investigation a liquid ionization chamber has been used as a transfer instrument for the quantity absorbed dose in water in a cobalt-60 gamma-ray beam. The characteristics of the liquid ionization chamber are described. The transferred dosimetric information has been compared with absorbed-dose determination using air-ionization-chamber dosimetry, water calorimetry and ferrous-sulphate dosimetry. The agreement between the different measured absorbed-dose values is very good, i.e. within 0.2%. This is an indication that the consistency in the methods used to determine absorbed dose in water is good. The impact of the new standard for air kerma in air, introduced in 1986 by the BIPM, on the air-ionization-chamber dosimetry is investigated. It is shown that any differences in the dosimetry when using the old or the new set of data cancel out for the cobalt-60 beam. The investigation also shows that the value of $\varepsilon_m G$ for the ferrous-sulphate dosimeter recommended in ICRU 35 for electrons can be used also in cobalt-60 beams.

Key words: Absorbed dose, water, cobalt-60, air-ionization-chamber, water calorimetry, ferrous-sulphate dosimeter, comparison.

Some standards laboratories are today developing standards for absorbed dose in water at a specified point in a water phantom for different photon-beam energies. The primary measurements are made in graphite using a graphite calorimeter. A transfer from graphite to water is then carried out making use of air-ionization-chamber measurements in the two mediums in combination with theoretically-based corrections (1–3). It should then be possible for a hospital physicist to go to the standards laboratory for the calibration of a transfer instrument (generally an ionization chamber) in the quantity absorbed dose in water and after the return to the hospital make his own calibrations. Most transfer instruments used today have an energy dependence in the beam-quality region of interest. In this case it is of great importance that the beam qualities and measuring conditions be very similar at the standards laboratory and at the hospital. However, this is often not the case as the hospital needs a large number of beam qualities and the standards laboratory, due to practical reasons, must restrict its choice.

If an air-ionization-chamber calibrated in the quantity absorbed dose in water at a certain beam quality is to be used at a different quality, then a procedure similar to that recommended by e.g. NACP (4), AAPM (5) or IAEA (6) has to be used.

An improvement in the overall accuracy would be to use a dosimeter having smaller energy dependence than the ionization chamber in the beam-quality region of interest. Such dosimeters are the liquid ionization chamber, the water calorimeter, and the ferrous-sulphate dosimeter. The calibration factor, chemical defect, and $\varepsilon_m G$ respectively have to be determined in the calibration geometry. It should then be possible to use the dosimeters in high-energy photon and electron beams of different qualities. Unfortunately, the water calorimeter and ferrous-sulphate dosimeter are still considered to be very laborious to use.

In the present investigation, liquid ionization chambers have been used for transfer of absorbed dose in water in a cobalt-60 gamma-ray beam from a standards laboratory (National Bureau of Standards, NBS) to two departments that have research programs in dosimetry. The advantages of the liquid ionization chamber are its small quality dependence and high reproducibility (7). The transferred

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Table 1

Comparison of absorbed dose calculation before and after 1986 January 1

	Before	After
Step 1		
Calibration in free air in a ^{60}Co gamma-ray beams in terms of air kerma in air: $N_K=K_{air}/M$	$N_K=1.000$ (normalized) value)	$N_K=0.9953$
Step 2		
Determination of absorbed-dose to-air calibration factor. (It is assumed that a cylindrical graphite ionization chamber is used and that the build-up cap + chamber wall together is 0.45 g cm^{-2}): $N_D=N_K\ (1-g)\ k_{att}\ k_m$	$k_{att}=0.990$ $k_m=0.991$ $1-g=0.9964$	$k_{att}=0.990$ $k_m=0.999$ $1-g=0.9968$
Step 3		
Determination of absorbed-dose--to-water at the effective point of measurement at the reference depth in a water phantom. (It is assumed that the chamber wall is 0.5 mm and that also the central electrode is made of graphite): $D_W(P_{eff})=M_u\ N_D\ (s_{w,air})_u\ P_u$	$(s_{w,air})_u=1.150$ $p_u=0.980$*	$(s_{w,air})_u=1.133$ $p_u=0.991$
Product of factors	1.102	1.102

*$p_u=0.970$ was given in NACP (4) for a graphite ionization chamber with internal diameter of 5 mm. p_u was then defined in connection with the use of the chamber center as the measurement point and includes therefore, a displacement factor equal to 0.990 (18). However, in IAEA (6) the use of an effective point of measurement is recommended. For the comparison the displacement factor should thus not be included in the NACP value.

dosimetric information has been compared with absorbed-dose determinations using air-ionization-chamber dosimetry, water calorimetry and ferrous-sulphate dosimetry. The present type of liquid ionization chamber is an improvement over that described by Wickman (8). This transfer system is very rapid and can easily be taken from one place to another.

Absorbed dose determination

Determination by NBS. At NBS, determination of absorbed dose in water in a ^{60}Co beam is based on measurements with a graphite calorimeter, transferred to a water phantom with a graphite thimble ionization chamber. The transfer required values of the ratio of the mean mass energy-absorption coefficients of water and graphite, obtained from published tables, and a correction for the replacement of water by graphite in the water phantom, obtained by experiment (1). The measurements were scaled from the graphite calorimeter to the water phantom by choosing the source-phantom distances, and the depths of measurements, so that the photon spectra at the measurement points would be essentially the same (2).

Determination by the Swedish group. Absorbed dose in water in a ^{60}Co beam was determined using the air-ionization-chamber method, the ferrous-sulphate method, and the water calorimeter method. The measurements were made at a 5-cm depth in water using a graphite ionization chamber. The field size was 20×20 cm and the source-to-phantom distance was 80 cm.

The *ionization-chamber method* has been based on the NACP protocol (4). The ionization chamber is to be calibrated in air kerma in air per unit scale division (N_K = K_{air}/M_c) at any of the Nordic secondary standards laboratories, step 1 in Table 1. They transferred their references (secondary standards) from the Bureau International des Poids et Mesures (BIPM). The basis of this dosimetry has recently been changed since the BIPM in the beginning of 1968 introduced a new standard for the air kerma in air. The reason for this change was the adoption of new stopping-power values reported in the International Commission on Radiation Units and Measurements (ICRU) Report No. 37 (9). However, in order to achieve consistency, new stopping-power values ought also to be introduced in the other steps of the absorbed-dose measurement chain, i.e. in step 2 (Table 1) where k_m (the non-air-equivalence correction factor for the material, m, in the ionization chamber and build-up cap) is computed using stopping-power data ($k_m = (s_{air,m}\ (\mu_{en}/\varrho)_{m,air})$, and in step 3 where $(s_{w,air})_u$ (the stopping-power ratio of water to air at the user's radiation quality u) and p_u (the total perturbation factor) are introduced. The value $(\mu_{en}/\varrho)_{m,air}$ is the mass energy-absorption coefficient ratio of the material to air. The values of μ_{en}/ϱ were obtained from Hubbell (10).

$$p_u = \frac{\alpha s_{wall,air}(\mu_{en}/\varrho)_{w,wall} + (1-\alpha)\, s_{w,air}}{s_{w,air}}$$

where α is the fraction of the total ionization produced by electrons from the chamber wall.

In Table 1 the dosimetry based on the calibration before 1986 and the application of NACP (4) is compared with the results using the current air kerma calibration from BIPM and new stopping-power values (from ICRU 37). The numerical values of k_m, p_u, and $(s_{w,air})_u$ computed from the new stopping-power values have been given by IAEA (6). Minor differences also appear as NACP (4) used the value of $g=0.0036$ from Boutillon (11), where g is the fraction of the energy of the secondary charged particles lost to bremsstrahlung in air.

The very interesting result from all these changes is that the final absorbed-dose values are equal, i.e. the product of all the factors is in both cases 1.1017 (see Table 1). This clearly indicates that differences between NACP (4) and IAEA (6) cancel out in this case for the ^{60}Co gamma-ray beam.

In Table 1, the other symbols are:

N_K air kerma calibration factor of an ionization chamber
K_{air} air kerma
M is the electrometer reading corrected for temperature and pressure
N_D is the absorbed-dose-in-air calibration factor
k_{att} is a factor correcting for attenuation and scattering in the ionization chamber material at the calibration
D_w is the absorbed dose in water
P_{eff} indicates the effective point of measurement
M_u is the electrometer reading in the user's beam corrected for temperature and pressure

The *ferrous-sulphate dosimetry* was carried out using a high-precision spectrophotometer. The calibration of the absorbance scale of the spectrophotometer has previously been investigated by intercomparison with spectrophotometers using potassium-dichromate solutions (12). The maximum deviation between the absorbances measured with the different instruments was 0.1%. In a further intercomparison organized by the CCEMRI (Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants), the NPL (National Physical Laboratory) supplied a certified reference material for absorbance standards (SRM 935). Measurements were made at 313 and 350 nm. The deviation at an absorbance of 0.2 ODU (optical density unit) was approximately 0.1% which is within the uncertainty of the intercomparison. The absorbance scale could therefore be used without corrections within an uncertainty of about 0.1%.

Table 2

Comparison of different methods for absorbed-dose determination for ^{60}Co gamma radiation as obtained by the Swedish team

Method:	FeSO$_4$ dosimetry	NACP (1980) (ion chamber)	IAEA (1987) (ion chamber)	Domen water calorimeter
D_w:	1.000 (normalized)	0.998	0.998	1.002

The absorbed dose was determined using the relation:

$$D_{FeSO_4} = \Delta A/(\varrho l \varepsilon_m G_m)$$

where

D_{FeSO_4} is the mean absorbed dose in ferrous-sulphate dosimeter solution
ΔA is the increase in absorbance at 304 nm due to irradiation
ϱ is the density of the dosimeter solution (1.024×10^3 kg/m^3
l is the length of the light path in the photometer cell (1.000×10^{-2} m)
ε_m is the molar extinction coefficient for ferric ions
G_m is ferric ion yield at the dose D_{FeSO_4}.

All measurements are referred to the temperature at the time of spectrophotometric evaluation, 25.0°C. (Corrections have to be applied at other temperatures; ref. 12).

The absorbed dose in water is determined from the equation

$$D_w = D_{FeSO_4}(\mu_{en}/\varrho)_{w,FeSO_4}.$$

The ratio of average mass energy-absorption coefficients for water to ferrous-sulphate dosimeter solution has been evaluated from Hubbell (10) and for ^{60}Co gamma radiation is 1.003.

$\varepsilon_m G = 352\cdot10^{-6}$ m^2 kg^{-1} Gy^{-1} was used for the absorbed-dose calculation. ICRU (7) states that the values for ^{60}Co gamma radiation and electron radiation should be approximately the same; the latter is given as $352\cdot10^{-6}$ m^2 kg^{-1} Gy^{-1}. This value also agrees closely with that reported by Svensson & Brahme (13), $353\cdot10^{-6}\pm3$ m^2 kg^{-1} Gy^{-1}.

Absorbed dose in water was also determined using the Domen type of water calorimeter (14–16). The construction and use follow that reported by these authors. This instrument gives the absorbed dose in water and requires knowledge of the heat defect. An exothermic heat defect of 3.5% was assumed (i.e. the instrument gives a larger signal than that corresponding to the absorbed dose)

Table 3

Characteristic data of the liquid ionization chamber of the design shown in Fig. 1

Parameter	Typical value
Volume of the radiation-sensitive liquid layer	≈2.9 mm^3
Thickness of the radiation-sensitive liquid layer	≈0.3 mm
Change in response per unit collecting voltage (at about 900 V)	0.046%/V
Increase in response with temperature	0.12%/K
Calibration factor for ^{60}Co gamma-ray quality given as absorbed dose to water at the center of the liquid layer (at 900 V and 22.0 °C)	≈0.063 Gy/nC
Residual current given as the equivalent dose rate in water at the center of the radiation-sensitive layer (at 900 V and 22.0 °C)	0.03–0.05 mGy s^{-1}
Recombination loss for continuous radiation	–
Change in response during one-year test (not including the first two weeks after liquid refilling)	<0.2%
Standard deviation of an individual measurement during a series of measurements at a dose rate of about 0.5 Gy min^{-1}	<0.1%

based on the comparison between graphite- and water-calorimetry measurements by Domen (15).

The absorbed-dose determinations based on these three methods were compared. The results were normalized to the absorbed-dose value determined using the ferrous-sulphate dosimeter. The absorbed-dose values based on the onization-chamber method and the Domen calorimeter were 0.2% lower and 0.2% higher respectively, than that from ferrous-sulphate dosimetry, see Table 2.

The standard deviations for the ionization-chamber, ferrous-sulphate, and calorimeter measurements were 0.1%, 0.2%, and 0.6% respectively. The observed differences are thus within the uncertainties of the measurements.

The transfer instrument

An important part of this investigation was the use of an improved liquid ionization chamber as a transfer instrument for absorbed-dose calibrations (8). In the present design (Fig. 1, Table 3), great emphasis was devoted to improve the robustness of the chamber. The chamber was made water-tight. The liquid of previous chambers had to be refilled after some months. Seven chambers with slightly different design details have now been used for more than one year without any refilling. Typically, the chamber response decreased about 1% during the first two weeks and then stabilized. It was shown that the chambers then have a very constant response, about ±0.1% (or less) change over a period of several months for the best-constructed chambers.

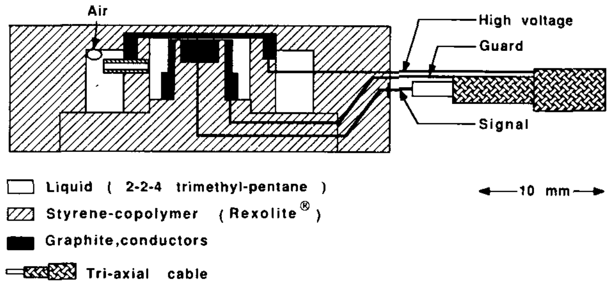

Fig. 1. The liquid ionization chamber. The data on the chamber are found in Table 3. The bubble in the chamber takes care of the different temperature expansion of the liquid and the plastic.

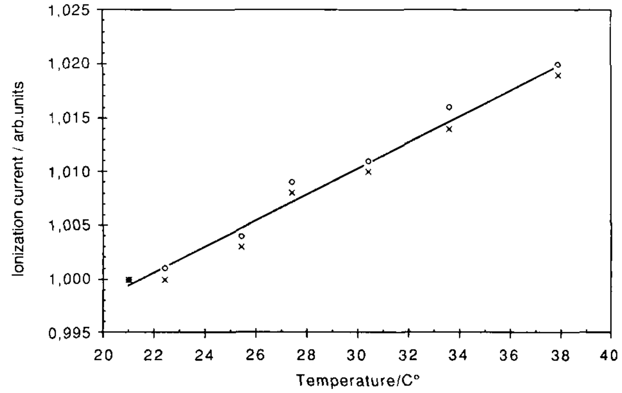

Fig. 2. Temperature dependence of the response of the liquid ionization chamber. ○ chamber No. 1; x chamber No. 2.

One great advantage of this chamber is the small dimensions of the sensitive volume. The diameter of the collecting electrode is 3 mm. It is separated from the guard electrode by 0.5 mm. The thickness of the sensitive liquid layer is only 0.3 mm.

The response of the chamber increases with the collecting potential. A collecting potential of 900 V was chosen because this gives a negligible general recombination loss for continuous radiation for dose rates generally used in radiation treatments (i.e. below 2 Gy min^{-1}). Corrections of the same magnitude as for common types of cylindrical air chambers must be carried out for pulsed radiation (8). The residual current (leakage) at this potential is still very small. With the present design of the chamber it corresponds to 0.03 to 0.05 mGy s^{-1}. The residual current is very stable and it is therefore generally sufficient to measure it at the beginning and at the end of an experiment. The residual current should be subtracted to determine the net signal.

The response of the chamber increases with temperature. A linear increase of 0.12%/K was obtained in the investigated temperature range of 20 to 40 °C (see Fig. 2). This value is only about half of that determined by Wickman (8) and Johansson & Svensson (17). The reason seems to be that in the old type of chamber a slight

Table 4

Calibration factors determined for the two liquid ionization chambers at NBS. The temperature varied between 21.83°C and 21.92°C. (The response change due to the temperature variation is thus insignificant.) The collecting voltage was 901.48 V

Source distance (m)	Water depth (mm)	Absorbed-dose rate (mGy/s)	Calibration factors (mGy/nC)
1.0000 (Chamber No. 1)	33.8	12.191	63.24
	51.9	11.438	63.27
	52.4	11.417	63.22
	53.2	11.382	63.21
	73.1	10.506	63.21
	93.6	9.596	63.26
	113.1	8.751	63.24
	131.4	7.990	63.26
Mean value:			63.24
1.0005 Chamber No. 2)	51.3	11.453	63.69
	73.4	10.482	63.71
Mean value:			63.70

Table 5

Intercomparison of absorbed-dose determination

Chamber	Calibration factor determined by		Difference
	NBS (mGy/nC)	Swedish team (mGy/nC)	
No. 1	63.24	63.23	−0.02%
No. 2	63.70	63.82	+0.19%

increase of the liquid-layer thickness was obtained due to the different expansion of the liquid and the plastic. In the present type a small air bubble was introduced in a side cavity to the sensitive layer. The size of this bubble changes with temperature thereby compensating for the difference in expansion. This construction also improves the precision of the chamber. The precision in the measurements is approximately the same as with a high-quality air-ionization-chamber.

Absorbed-dose intercomparison between NBS and the Swedish group

Two liquid ionization chambers were used as transfer instruments for absorbed-dose intercomparisons. The chambers had been calibrated in a ^{60}Co gamma-ray beam by the Swedish team and brought to NBS. A very similar measurement procedure as for an air ionization chamber could be used. NBS investigators thus used their power supply for the collection potential (901.5 V) and their electrometer for measurement of the collected charge from the liquid chamber. The center of the sensitive liquid layer of the chamber was placed at a distance of 1 m from the source. The absorbed dose in water determined by the two teams was to be compared. The field size at the position of the chamber was 144×144 mm and the depth of water was varied.

A blind intercomparison was made, i.e. the dose rates at the depth of interest were not known during the measurements at NBS. The chambers were then brought back to Sweden and were checked for constancy. The change in response was less than the measurement precision, i.e. 0.1%. The absorbed-dose values based on the calibrations in Sweden were reported to NBS. NBS mailed at the same time the results of their measurements (Table 4). It is seen that the calibration factor of the liquid ionization chamber is not dependent on the phantom depth. The mean values are compared with the values determined by the Swedish team in Table 5. The Swedish team determined their calibration factors from the ferrous-sulphate dosimeter at a depth of 5.0 cm in water at 144×144 mm field size. (The air ionization chamber dosimetry or the Domen water calorimeter would have given only slightly different values; see Table 2.) The factors refer to the same water temperature and collecting voltage.

Discussion

The investigation shows that the three dosimetric methods used by the Swedish team give, within the uncertainty of the measurements, the same absorbed dose in water when used in a ^{60}Co gamma-ray beam. The good agreement between the different systems can be regarded as a check of the consistency of the total dosimetry system. All three systems, independent in practice, are in different ways related to graphite-absorbed-dose calorimetry. For the air-ionization-chamber, the W/e value is determined from measurements with a graphite calorimeter. For the water calorimeter the heat defect is based on measurements with a graphite calorimeter and for the ferrous-sulphate dosimeter the $\varepsilon_m G$ value given in ICRU 35 (7) is to a large extent based on measurements with a graphite calorimeter.

The intercomparison between the dosimetric methods applied by NBS and the Swedish team using the liquid ionization chamber shows a very good agreement. Thus the absorbed-dose-in-water determination based on the ferrous-sulphate method by the Swedish team differed less than 0.2% from that based on the graphite-calorimeter measurements by the NBS team. The difference is within the experimental uncertainty. The investigation shows that the $\varepsilon_m G$ value for the ferrous-sulphate dosimeter recommended in ICRU 35 (7) for electrons can also be used in ^{60}Co beams. The result of the water-calorimeter measurements shows that the water calorimeters used by the two teams have the same performance in ^{60}Co beams. It is shown that the liquid ionization chamber is well suited as a transfer instrument. The chamber is very simple to apply and measuring equipment already available at most laboratories can be used. An obvious advantage with the chamber is the fact that it is very suitable for calibration of the quantity absorbed dose in water. Its very weak quality dependence (if any) for high-energy photon and electron radiation (17) makes the chamber a very convenient instrument to be used at a hospital. The quality dependence needs to be carefully studied and further experiments are needed to make the chamber usable also for departments other than that involved in the construction of the chamber.

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Request for reprints: Dr G. Wickman, Radiation Physics Department, University of Umeå, S-901 85 Umeå, Sweden.

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