Radial non-uniformity of the BIPM ^{60}Co beam

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Abstract

The radial non-uniformity of the ^{60}Co BIPM beam has been evaluated both theoretically and experimentally, in air and in a water or graphite phantom. The correction factors for this effect, pertinent to detectors used for the measurement of absorbed dose, have been determined. The results are given with an uncertainty of 0.03 %.

1. Introduction

The absolute determination of absorbed dose in graphite or water is performed at the Bureau International des Poids et Mesures (BIPM) by means of a flat cylindrical ionization chamber 4.5 cm in diameter, located inside a phantom and centered perpendicularly to the beam axis [1]. To obtain this quantity the measurements have to be corrected for the radial non-uniformity of the beam over the chamber cross section. The beam non-uniformity is evaluated either experimentally or theoretically.

2. Conditions of measurement

The geometrical conditions used for the measurement of absorbed dose are those recommended by the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) [2]. They are:

- source-to-reference plane distance = 1 m,
- beam cross section in the reference plane = 10 cm x 10 cm.

The graphite phantom is a cylinder 30 cm in diameter and 20 cm long. The density of the graphite is 1.80 g cm^{-3}. The reference depth for the measurement of absorbed dose in graphite is 5 g cm^{-2}. For measurements at other depths the standard chamber remains in its position in the reference plane and graphite plates are added in front of the phantom.

For measurements of absorbed dose to water the BIPM uses a cubic water phantom, 30 cm on a side. The reference plane (at 1 m from the source) is at a depth of 5 g cm^{-2}. For measurements at other depths in water the detector is shifted inside the phantom (kept fixed) along the beam axis. Thus the beam cross section varies with depth.

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3. Radial beam non-uniformity in air or in a water phantom

The non-uniformity of the beam has been measured in air and in the BIPM water phantom at depths of 5 and 17 g/cm^2 by means of a small spherical ionization chamber (internal diameter 3 mm). The beam non-uniformity is given by the variation of the chamber response, when it is shifted laterally from its reference position on the beam axis. The results are given in Figure 1. The experimental uncertainty (of about 0.03 %) is mainly due to air temperature fluctuations when the chamber is in air and to small variations of positioning when the chamber is in water.

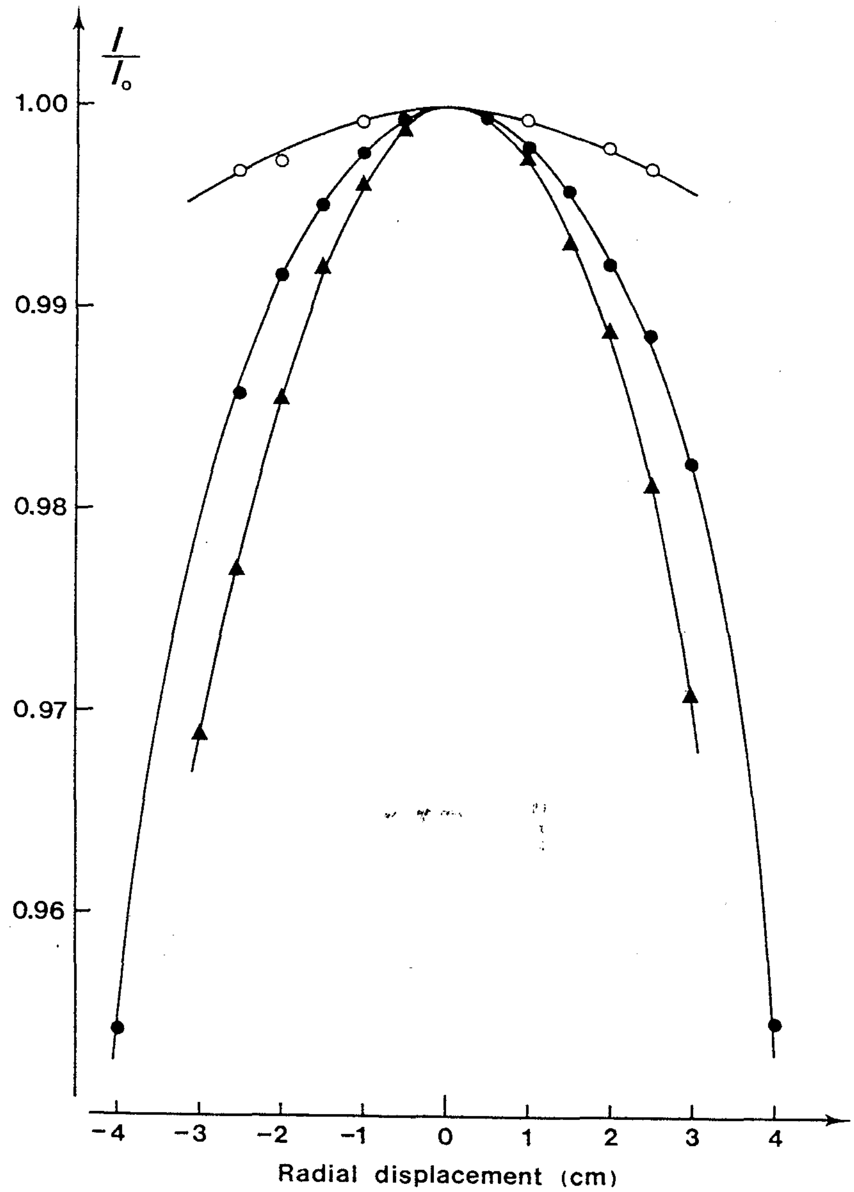

Fig. 1 - Variation of the ionization current I for the radial displacement of the small spherical chamber.

o : in air, ● : in water at 5 g cm^{-2}, ▲ : in water at 17 g cm^{-2}

The radial non-uniformity of the beam in air is due to the finite source dimension, the scattering environment and the collimation system. As seen in Figure 1, the decrease of the detector response at the reference plane in air is rather small, at least for a radial displacement of up to about 3 cm.

In the water phantom this decrease is more important, particularly at large depths. The non-uniformity of the beam, for a given depth inside the water phantom, is not only due to the primary photons, but also to those which are scattered in the phantom. The primary beam in the reference plane has the same non-uniformity in the phantom as in air and the non-uniformity of the radiation scattered in the phantom depends on that of the primary one and also on other parameters, the most important ones being the size of the beam cross section and the geometrical depth.

This is shown in Figure 2, where we consider the photons emitted by the source which are scattered in the volume dv (cross section S and thickness dz). For those which can reach the small sphere A_o on the beam axis, the trajectories are within the solid angle Ω (see for example the photon scattered in P_1). When A_o is shifted away from the axis (at position A_1), the same solid angle Ω starting from A_1 intercepts a part S_1 of the surface S. Photons coming from the part S_2 can also reach A_1, but they have a scattering angle larger than those included in Ω (see for example the photon scattered in P_2, for which we have $\theta > \theta_o$). Their probability of production and their energy are smaller and they undergo more attenuation between z and z_o. Hence, the energy fluence due to photons scattered in the volume dv is lower at A_1 than at A_o.

This difference increases rapidly with decreasing beam cross section and leads to a non-uniformity which is usually much larger for the scattered radiation than for the primary one. We note that for an infinite beam cross section, the non-uniformity of the scattered radiation would be smaller. This difference increases too with the distance between z and z_o. As a consequence, the non-uniformity of the scattered radiation in the plane z_o will increase with the geometrical thickness of material in front of z_o. The influence of these two parameters on the non-uniformity of the scattered radiation can be checked experimentally, as will be shown in Section 5.

In the above considerations attention has been given only to first-order scattered photons. The effect of multiply-scattered photons on the beam non-uniformity is less easy to estimate, but it is probably of less importance.

Other parameters may also contribute to the beam non-uniformity, such as the electronic density and the density of the phantom material. No systematic study has been made, however, concerning their influence since the problem is outside the scope of the present work.

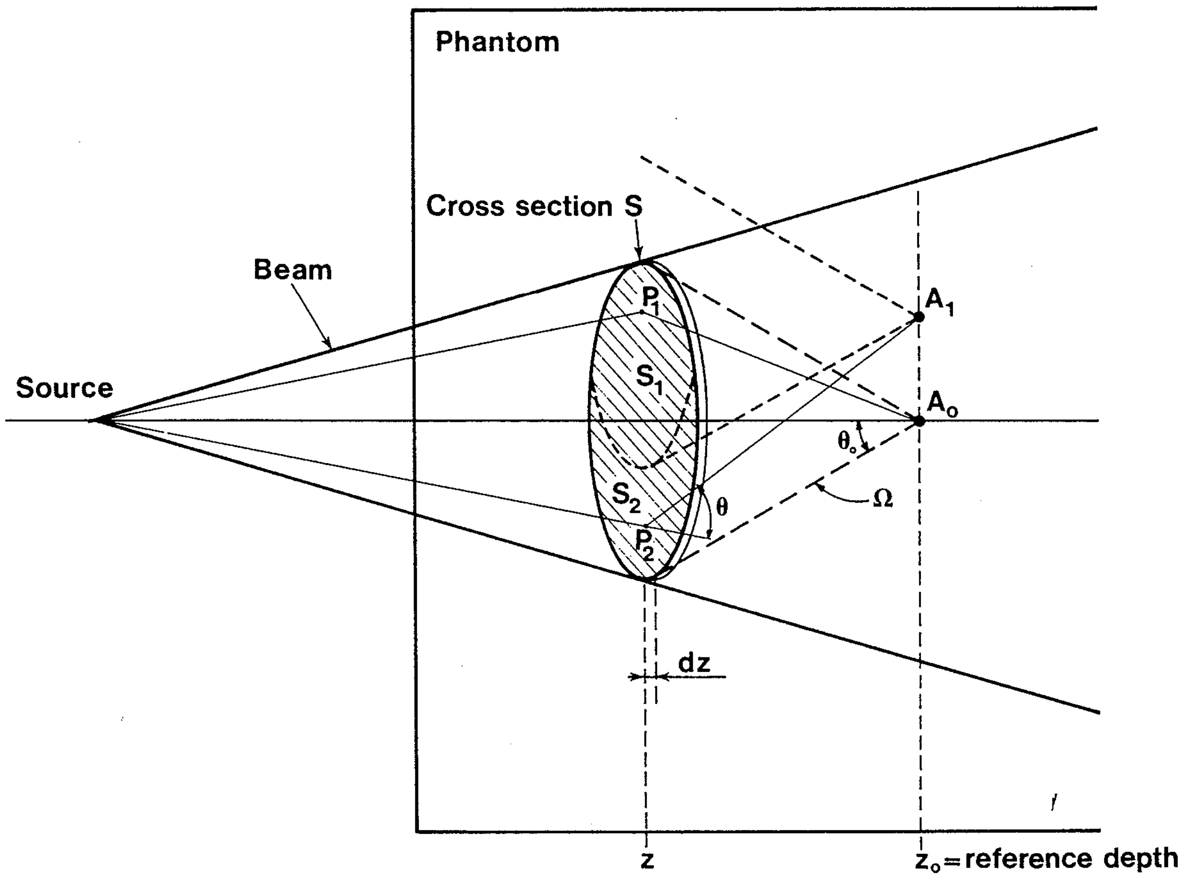

Fig. 2 - Schematic representation of the first order scattered photons.

4. Radial beam non-uniformity in a graphite phantom

The experiment is less easy to perform in the case of a graphite phantom as it is hardly possible to shift a small ionization chamber in such a phantom. Only one experiment is possible which consists in shifting the whole assembly phantom + standard chamber. However, there are two limitations for the interpretation of the results thus obtained. First, it is a priori not obvious that shifting the whole assembly would give the same results as displacing a small chamber inside the graphite phantom. Second, since the BIPM standard is 4.5 cm in diameter, we can hardly speak of point measurements, and it is well known that the deconvolution of experimental data may lead to substantial uncertainties. In fact, such experiments have been made, but only for checking purposes.

For the determination of the beam non-uniformity in a graphite phantom, we have used a Monte Carlo simulation method. In this calculation the non-uniformity of the beam, as experimentally determined in air, has been applied to the beam entering the phantom, and the amount of scattering present in the primary BIPM beam (18 % in terms of energy fluence) has been taken into account. For verification, the method was first applied to the determination of the beam non-uniformity at a depth of 5 g cm^{-2} in the water phantom. We give in Figure 3 the calculated values of the correction factor for radial non-uniformity, k_{rn}, to be applied to the response of a detector, centered on the beam axis, as a function of its radius r. The random uncertainty of k_{rn} is about 0.03 %. The curve in this figure is obtained from the experimental measurements in water (see Section 3) and we can note an excellent agreement between the experimental and calculated data.

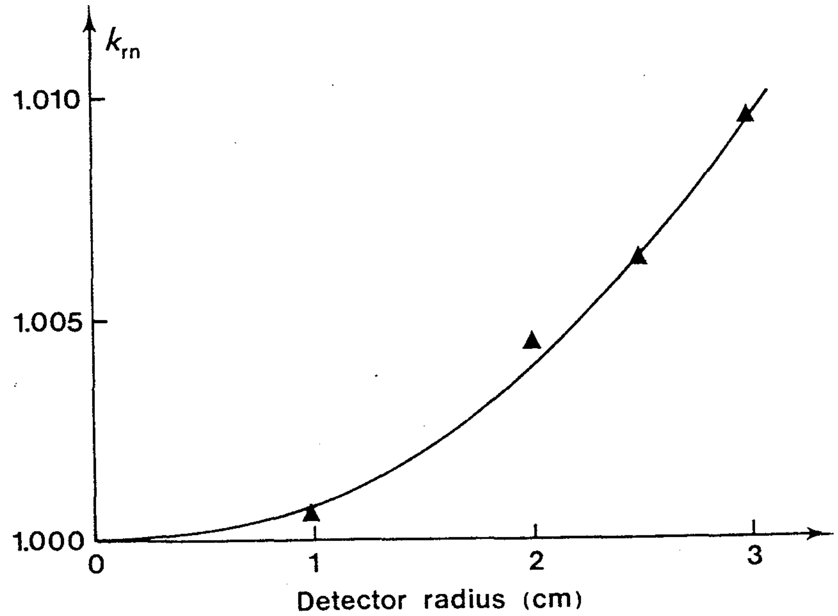

Fig. 3 - Beam non-uniformity correction factor k_{rn} in a water phantom.
▲ : Calculation, —— : Experiment.

The same method has then been used for the evaluation of the beam non-uniformity in the graphite phantom, for a radius ranging from 0 to 3 cm. Calculations were performed with 15 to 30 million photon histories (depending on the depth in graphite) in order to achieve a statistical uncertainty not exceeding 0.03 %. Depths in graphite from 1 to 17 g cm^{-2} were considered. As an example, Figure 4 shows the variation of the correction factor for beam non-uniformity, k_{rn}, as a function of the detector radius r and for the depths 5 and 17 g cm^{-2} in the graphite phantom.

From these results we have derived the variation in the response of the BIPM standard chamber as a function of a lateral displacement from its centered position on the beam axis. The results are given in Figure 5 together with experimental data obtained by moving the phantom away from the beam axis. The agreement between the two sets of results is good and tends to support our belief that the determination of the beam non-uniformity in the BIPM graphite phantom is reliable.

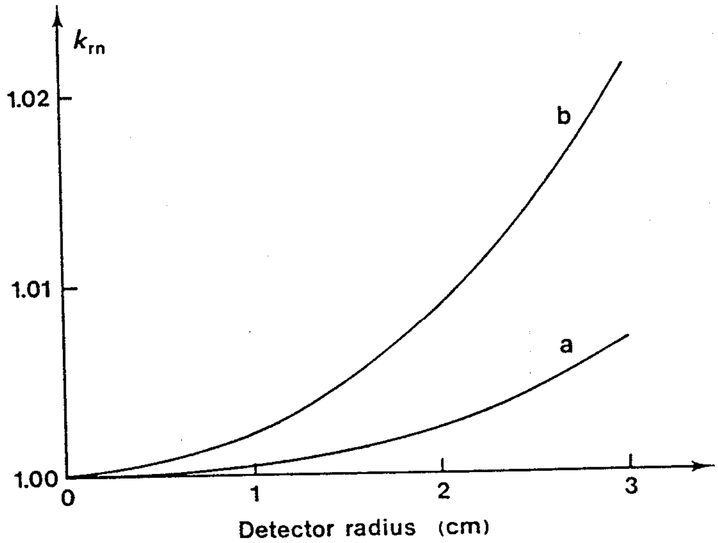

Fig. 4 - Beam non-uniformity correction factor k_{rn} in a graphite phantom.
a depth = 5 g cm^{-2}, b depth = 17 g cm^{-2}.

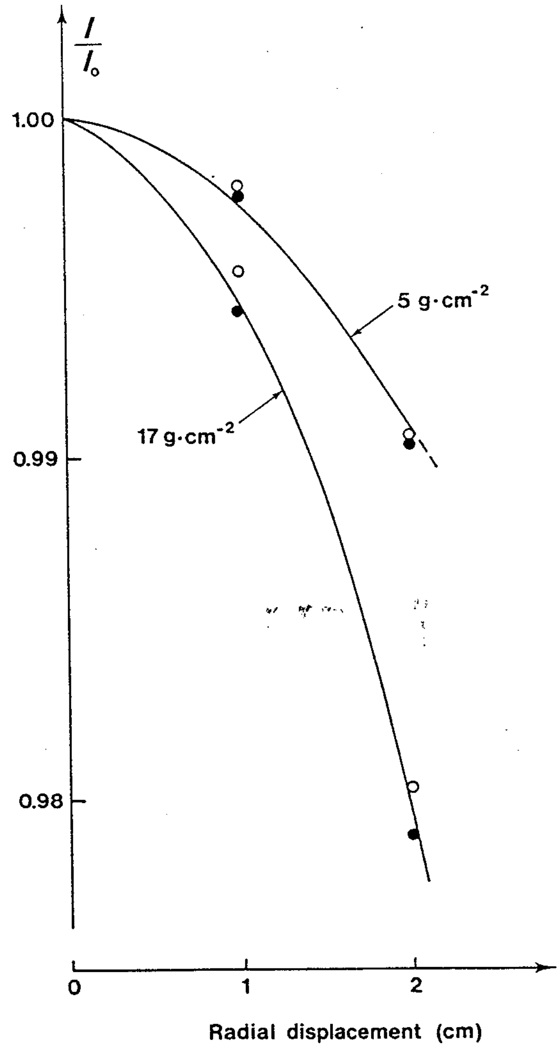

Fig. 5 - Variation of the ionization current I for radial displacememnt of the BIPM standard in the graphite phantom.
Calculated : ——; Experiment : o, • (for symmetrical displacements).

5. Discussion

In Table 1 we list for comparison some of the main results obtained for water and graphite. As already noted, k_{rn} increases with depth, i.e. with the amount of scatter given in terms of R, the ratio of the kermas produced by the scattered and the primary radiations. The table also clearly shows the strong dependence of k_{rn} on the beam cross section.

Table 1

Beam non-uniformity correction factor, k_{rn}, for the BIPM standard

Variation of k_{rn} with R *

	depth ($g\ cm^{-2}$)	R	k_{rn}
water	5	0.24	1.0051
	17	0.53	1.0083
graphite	5	0.27	1.0032
	11	0.48	1.0065
	17	0.63	1.0114

Variation of k_{rn} with the beam cross section

	depth ($g\ cm^{-2}$)	beam cross section (cm x cm)	k_{rn}
graphite	5	10 x 10	1.0032
	5	9.3 x 9.3	1.0045
	17	10 x 10	1.0114
	17	5 x 5	1.040

* R is the ratio of the kermas produced by the scattered and the primary radiations.

The values of k_{rn} for the BIPM standard as a function of depth in graphite are given in Figure 6. The curve (a) refers to the usual conditions of measurement (see Section 2), whereas curve (b) is obtaibed for a fixed position of the graphite phantom. The difference between the two curves, at a given depth, is due to the difference in the beam cross sections. We may note that at depth $z = 0$ the value of k_{rn} in curve (a) is slightly higher than the corresponding value obtained in air (for the same distance and beam cross section). This small increase is due to the effect of the backscatter from the graphite phantom.

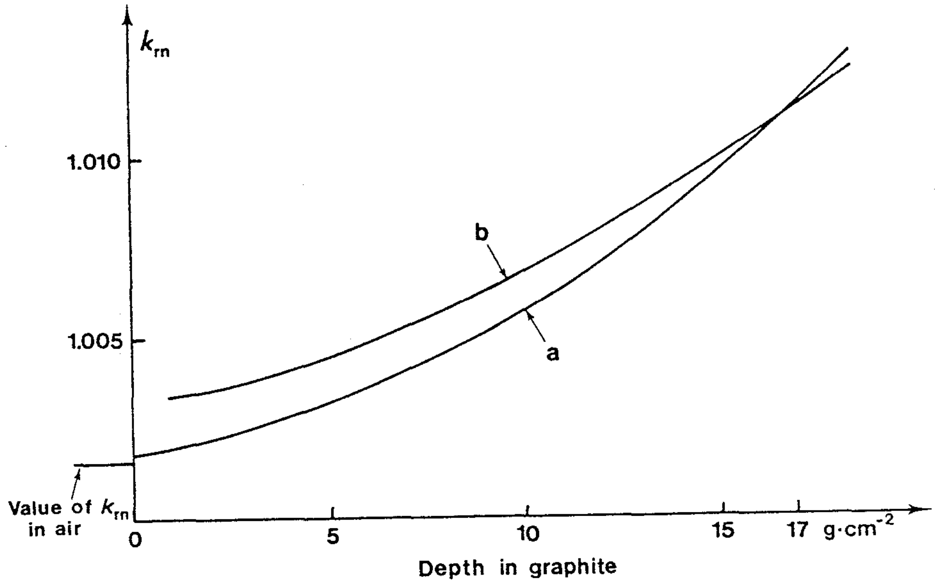

Fig. 6 - Beam non-uniformity correction factor k_{rn} in a graphite phantom.
a Chamber fixed (usual conditions, see Section 2),
b Phantom fixed, reference plane at a depth of 17 g cm^{-2}.

We can also note the trend of curve (a) which rises, as a function of depth, more than linearly. The relation between R and k_{rn}, for a given beam cross section, is not linear. This is due to the influence of the geometrical depth on the non-uniformity of the scattered radiation, as already mentioned.

This effect also explains, at least in part, the difference between the k_{rn} values obtained in water and graphite (see Table 1) at a given depth (5 g cm^{-2}), distance to the source (1 m), beam cross section (10 cm x 10 cm) and value of R, but for different geometrical depths (5 and 2.8 cm, respectively).

6. Conclusion

The method of calculation used for the determination of the beam non-uniformity in a graphite phantom has been found to be both useful and sufficiently precise. The results are obtained with an uncertainty of about 0.03 %, which is comparable to the uncertainty of the experimental determination of the beam non-uniformity in air or in a water phantom. Comparisons made between experimental and calculated data show in all cases a very good agreement.

In addition, the main causes responsible for the variation of the beam non-uniformity in a phantom have been identified and a qualitative explanation of their influence is given.

References

[1] Niatel, M.-T., On the location of a flat ionisation chamber for absorbed dose determination, Phys. Med. Biol. 1983, 28, pp. 407-410

[2] BIPM Com. Cons. Etalons Mes. Ray. Ionisants (Section I) 5, 1979, p. R(I) 5.

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