Experimental derivation of the fluence non-uniformity correction for air kerma near brachytherapy linear sources

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In brachytherapy, one of the elements to take into account for measurements free in air is the non-uniformity of the photon fluence due to the beam divergence that causes a steep dose gradient near the source. The correction factors for this phenomenon have been usually evaluated by two available theories by Kondo and Randolph [Radiat. Res. **13**, 37–60 (1960)] and Bielajew [Phys. Med. Biol. **35**, 517–538 (1990)], both conceived for point sources. This work presents the experimental validation of the Monte Carlo calculations made by Rodriguez and deAlmeida [Phys. Med. Biol. **49**, 1705–1709 (2004)] for the non-uniformity correction specifically for a Cs-137 linear source measured using a Farmer type ionization chamber. The experimental values agree very well with the Monte Carlo calculations and differ from the results predicted by both theoretical models widely used. This result confirms that for linear sources there are some important differences at short distances from the source and emphasizes that those theories should not be used for linear sources. The data provided in this study confirm the limitations of the mentioned theories when linear sources are used. Considering the difficulties and uncertainties associated with the experimental measurements, it is recommended to use the Monte Carlo data to assess the non-uniformity factors for linear sources in situations that require this knowledge. © *2008 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2940160]

Key words: brachytherapy dosimetry, ionization chambers, linear sources

I. INTRODUCTION

The reference air kerma rate of a source is defined as the kerma rate to air, in air, at a reference distance of 1 m, corrected for air attenuation and scattering.[1]

In the calibration laboratories a large volume secondary standard ionization chamber, such as the 1000 cc PTW model LS-01, is usually used as a standard for measurements of air kerma strength free in air.

As discussed by Bielajew,[2] in order to assess the exposure and air kerma, the axial and radial non-uniformity perturbation must be taken into account for the non-uniformity of the photon field near the chamber cavity.

In the clinical environment, measurements at short distances face three practical problems: first, the low sensitivity of the electrometers to the signal generated by the source in a small chamber volume and when the detector is located at the recommended distance, second, the non-uniformity of the fluence over the chamber's volume, and third, the experimental setup is very critical in order to reduce the major uncertainties associated with the chamber positioning.

For those reasons it is recommended in the clinical environment to use a well type chamber with its calibration coefficient traceable to a secondary standard calibration laboratory.

Several authors have addressed these problems for measurements with small thimble type Farmer chambers and a procedure has been suggested by Aukett[3] to measure the air kerma rate for small spherical Cs-137 sources at short distances. Deshpande and Wilkinson[4] provided some experimental data for Cs-137 pellets and Tölli *et al.*[5] measured correction factors for a very small, almost punctual, Ir-192 HDR source. Theoretical non-uniformity correction factors have been calculated by Kondo and Randolph[6] using several assumptions to justify as isotropic the secondary electrons generated in the internal chamber wall and Bielajew[2] considered the anisotropic angular fluence distribution of the secondary electron inside the chamber. Both theories were developed for point sources and, recently, Rodriguez and deAlmeida,[7] using the PENELOPE Monte Carlo code, have found non-negligible deviations when a linear source is used.

In this work the non-uniformity of the photon fluence correction for a 0.6 cc Farmer type thimble chamber was experimentally determined for a Cs-137 low dose rate linear source using the same calculation geometry as Rodriguez and deAlmeida[7] and compared with the experimental and theoretical results previously reported for point sources.

II. MATERIAL AND METHODS

A Cs-137 linear source model CDCS J4, with 13.5 mm active length, 2.0 cm total length, 0.265 cm external diameter, and an air kerma rate of 99.69 μGyh^{-1} at the reference distance of 1 m, was used in this work.

The measuring devices were an ionization chamber Farmer type NE model 2571 with a nominal volume of 0.6 cc, a Delrin build-up cap 0.387 cm (0.551 g cm^{-2}) thick, and a Keithley electrometer model 3540.

The chamber was mounted in a remote controlled MedTec-150-M displacement system for the chamber posi-

TABLE I. The correction factors determined in this work compared with those provided by other authors.

		Non-uniformity correction factors			
Source to chamber distance (cm)	Experimental values (This work)	Deshpande and Wilkinson (Ref. 4)	Kondo and Randolph (Ref. 6)	Bielajew (Ref. 2) (ω=0.992)	Rodríguez and deAlmeida (Ref. 7)
1.00	1.315 ± 0.009 [a]	1.290[b]	1.344	1.359	1.307
1.01	1.310 ± 0.008	-	1.339	1.355	1.303
1.25	1.201 ± 0.008	-	1.242	1.259	1.211
1.50	1.137 ± 0.009	1.180	1.179	1.198	1.139
1.75	1.109 ± 0.008	-	1.139	1.157	1.099
2.00	1.076 ± 0.008	1.090	1.111	1.128	1.066
2.25	1.060 ± 0.006	1.071	1.091	1.106	1.056
2.50	1.042 ± 0.003	1.060	1.074	1.089	1.034
3.00	1.029 ± 0.005	1.048	1.051	1.065	1.034
3.50	1.017 ± 0.007	1.040	1.039	1.051	1.024
4.00	1.000 ± 0.008	1.030	1.031	1.042	1.010
5.00	0.998 ± 0.008	1.012	1.020	1.029	1.003
6.00	0.997 ± 0.007	0.996	1.013	1.021	1.001
7.00	1.000 ± 0.003		1.010	1.017	1.000

[a] Extrapolated value from the measurements.
[b] Extrapolated value from the curve.

tioning with a resolution better than 0.01 cm. The horizontal positioning of the system was verified regularly during the experiment by using a vertical level.

The system was fixed on a plastic holder at a distance of 100.0 cm from the room walls and floor in order to minimize the room scattering contribution to the signal.

The chamber was placed with its longitudinal axis perpendicular to the source long axis and the working distances varied from 1.01 to 7.00 cm where the effect becomes negligible. The instrumentation warm-up time was about 2 h and the integration time varied from 2 min at short distances to a maximum of 26 min for the longer distance in order to obtain a good signal.

Temperature, humidity, and pressure sensors were installed near the chamber and the air mass in the chamber was corrected for the reference conditions for each individual charge signal collected as well as for the instrument leakage. The relative humidity was kept around 50% during the measurements, hence no correction was needed.

The experiment was repeated on seven different occasions and the reproducibility was better than 0.2%.

The numerical value of the non-uniformity correction for the fluence was obtained using the expression below, which was proposed by Tölli and Johansson:[8]

$$K_{\mathrm{ln}}(x_1) = \frac{x_2 M(x_2) G_F(x_1) \tan^{-1}[L/2x_1]}{x_1 M(x_1) G_F(x_2) \tan^{-1}[L/2x_2]},$$

where $M(x)$ is the ionization reading at a distance x in cm from the source and chamber centers, respectively, ignoring air attenuation and scatter, L is the source active in cm, and $G_F(x)$ is the source and capsule filtration factor. $\tan^{-1}$ considers the finite source size. The index ln is used to indicate that the correction factor is determined for a linear source.

II.A. Correction for room scattering

It has been shown by Drugge[9] that, for measurement at distances greater than 20.0 cm from any scattering material, the room scatter contribution is negligible. For this reason, no correction was made for the scatter in the experimental arrangement used. The scatter contribution from the plastic holder was verified by moving the source support and chamber away to three distances apart (5.0, 7.0, and 10.0 cm) and the measured effect was negligible.

II.B. Correction for attenuation in the build-up cap and wall

The scatter and attenuation of the photons (Awall) in the inner wall and cap of the chamber are distance dependent as described by Bielajew and Rogers[10] and are part of the experimental determination of the K_{ln}. This contribution was evaluated for source-to-chamber distances from 1 to 7 cm and the appropriate corrections are included. The shape of the curve is similar to the one reported by Tolli *et al.*[5]

II.C. Effect of the central electrode and the geometric point of measurement

As extensively discussed by Tölli *et al.*,[5] there has not been found any significant effect of the central electrode on the non-uniformity correction factors and, for this reason, it was not evaluated in this study. A possible change in the position of the geometric center of the chamber was verified by moving the chamber 0.1 cm in both axes and there was found no measurable effect for the ranges of distances used in this work.

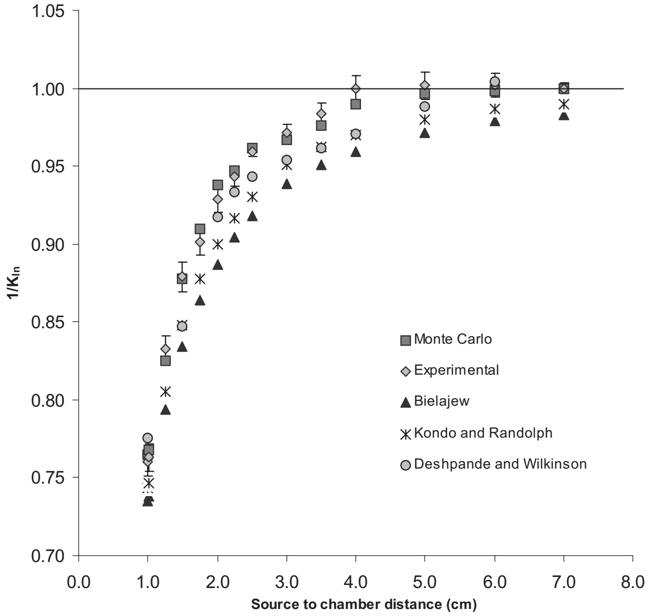

FIG. 1. The photon fluence non-uniformity fluence correction measured for a linear source compared with similar results assessed by Monte Carlo and the data reported for point sources.

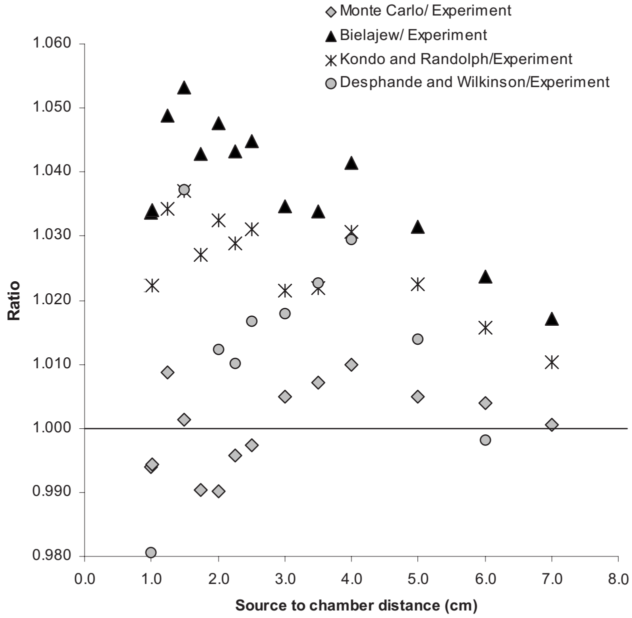

FIG. 2. The ratio of the theoretical to experimental measurements of the non-uniformity correction factors for the NE2571 chamber.

III. RESULTS AND DISCUSSION

The numerical values of the non-uniformity correction experimentally measured in this work for a linear source and for various source-chamber distances are presented in Table I. The results have shown correction values for the NE 2571 chamber of 0.760 for the distance of 1.0 cm, 0.971 for 3.0 cm, and 1.002 for 5.0 cm.

A strong correlation can be observed between these values and the ones reported by Rodriguez and deAlmeida.[7]

As predicted, the non-uniformity corrections are larger at short distances, reducing drastically from about 32.0% to 3.0% at distances of 1.0 to 3.00 cm, respectively. For distances greater than 4.0 cm, the source to chamber distance becomes much larger than the source dimension or the chamber dimensions and that makes the beam behave much like a parallel beam and the correction value tends to unity.

Figure 1 shows the overall shape of the curves and Table I presents the numerical values of the experimental results of this work, the Deshpande and Wilkinson[4] results for Cs-137 pellets, the calculated values for point sources by Kondo and Randolph[6] using the isotropic theory, the ones calculated by Bielajew[2] using the anisotropic theory, and the Monte Carlo data reported by Rodriguez and deAlmeida.[1] For Bielajew's data the degree of anisotropy of the electron fluence, ω, was taken to be equal to 0.992 as suggested by Tölli *et al.*[5]

This comparison with the present results clearly indicates that both the isotropic and the anisotropic theories slightly overestimate this correction when applied to linear sources. This effect is emphasized in Fig. 2, which shows the ratio between the experimental results obtained in this work, the results of the Monte Carlo simulations, and previously published results from various authors. Table II presents the numerical values related to Fig. 2.

III.A. Experimental uncertainties

In this study, the relative measurements carried out at close distances to the source, and especially the source to chamber distance determination, are the predominant sources of uncertainties to be considered.

The linearity of the chamber positioning system verified for the range of 1.0 to 17.0 cm in both directions was consistently better than 0.01 cm with a correlation coefficient of 0.9999. The repeatability of the chamber positioning measured with a thin gauge calibrated by a digital caliper was better than 0.006 cm. The overall combined uncertainty[11] in the distance was estimated as 0.012 with $k=1$.

IV. CONCLUSIONS

In this study the non-uniformity correction factors due to the fluence divergence near brachytherapy linear sources were experimentally measured. The results validate the calculated values done with Monte Carlo by Rodriguez and deAlmeida[7] and confirm the deviations from both available theories conceived for point sources.

Both theories and the experimental results of Desphande and Wilkinson[4] overestimate the correction factor when compared to linear sources. The difference can be as high as 5.3% and 3.2% for the anisotropic theory, 3.7% and 2.2% for the isotropic theory, and 3.0% and 1.9% for the experimental data of Desphande and Wilkinson[4] for the distances of 1 and 5 cm, respectively.

The results also support the premise that the variation of the photon fluence in the chamber wall depends on the source and chamber dimensions but, more importantly, the source-chamber distance.

A thimble type ionization chamber NE 2571, a 35040 Keithley electrometer, and a remote controlled chamber po-

TABLE II. Numerical values used in this work for the calculation of K_{ln}.

Distance (cm)	Measuring time (min)	Average charge collected (nC)	Average value K_{ln}
1.011	2	0.5051 ± 0.0027	1.3201
1.250	2	0.3872 ± 0.0034	1.1708
1.500	2	0.2876 ± 0.0038	1.1236
1.750	2	0.2225 ± 0.0031	1.0850
2.000	3	0.2632 ± 0.0041	1.0663
2.250	3	0.2122 ± 0.0036	1.0537
2.500	4	0.2346 ± 0.0059	1.0365
3.000	6	0.2495 ± 0.0008	1.0256
3.500	7	0.2180 ± 0.0048	1.0114
4.000	9	0.2172 ± 0.0054	1.0026
5.000	14	0.2224 ± 0.0047	0.9813
6.000	19	0.2117 ± 0.0062	0.9828
7.000	26	0.2167 ± 0.0014	1.000

sitioning device with a good reproducibility in the chamber positioning were the main components of the experimental setup. The experimental uncertainties were evaluated for the physical parameters involved, the chamber positioning being the most critical one. The combined overall uncertainty in the correction factor determined experimentally is better than 1%.

In order to accurately measure the air kerma free in air with ionization chambers near brachytherapy sources where steep dose gradients may be found, a correction factor must be applied that is specific for the source used and the distance under consideration. Considering the complexity of the experimental setup, the careful signal to noise ratio, the accuracy of the positioning device, and, in the absence of an analytic theory, the Monte Carlo technique with appropriate inputs can very useful to derive the appropriate corrections for linear sources with different dimensions and wall materials. However, in the clinical environment the use of a well type chamber is strongly recommended.

Since the inverse square law effect predominates over scattering and absorption for short distances, the results might be also applicable to dose measurements in water.

The application of these corrections will minimize unnecessary additional uncertainties related to the standards used for source calibrations with an indirect impact in the dose delivered to the patient.

Limitations of the isotropic and the anisotropic theories have been demonstrated when they are used to linear sources. In clinical practice, the TG-43 formalism[12] used in commercially available treatment planning systems yields the dose around brachytherapy sources from data derived by Monte Carlo calculations experimented validated by TLD measurements by Perez-Calatayud *et al.*[13]

The aim of this paper is to stress the need for accurate non-uniformity data when an ion chamber is used to measure air kerma or exposure near linear sources.

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