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INTERNATIONAL COMPARISONS OF IONIZATION CHAMBERS FOR ABSOLUTE MEASUREMENTS OF THE ROENTGEN AT PHOTON ENERGIES OF ABOUT 1 MeV

by

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Accuracy of dose determination is of great importance for many applications of ionizing radiations in radiation therapy, radiobiology, and radiation biophysics. The absorbed dose (rad) is at the moment generally determined by measuring the ionization in air and multiplying this by a conversion factor. For example in the U. K. there is a code of practice for the dosimetry of high energy roentgen and gamma ray beams which gives conversion factors for particular types of chambers calibrated with 2 MV roentgen rays (Hospital Physicists' Association 1964). Calibrations of commercial ionization chambers designated for use as secondary standards are carried out at regular intervals by the various state organizations using their own particular radiation standards.

The purpose of this paper is to report a direct comparison between the cavity ionization chambers of the Institute of Biophysics of the German Academy of Sciences of Berlin, G. D. R. (DAW) with those of the National Physical Laboratory, Teddington, U. K. (NPL) and with the pressure chamber of the Men-

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Table 1

International comparisons or calibrations of secondary standards of other countries with the DAW cavity ionization chambers

Country	Place of measurement	Institution	Time	Type of measurement
Hungary	Budapest	Oncological Institute, Budapest	July 1964	Measurement of ^{60}Co Unit Gravicert
Bulgaria	Berlin	Oncological Institute, Sofia	Jan. 1965	Calibration of Siemens dosimeter unit
CSSR	Prague	Institute for Nuclear Research, Prague	May 1965	Measurement of ^{60}Co source for the high-pressure chamber to be constructed
CSSR	Berlin	Institute for Nuclear Research, Prague	Nov. 1966	Calibration of two chambers as secondary standards
Hungary	Berlin	State Board of Metrology, Budapest	Nov. 1966	Calibration of two chambers as secondary standards

deleeff Institute, Leningrad, U. S. S. R. (VNIIM). These comparisons are of special interest for two reasons. Firstly, they enable a comparison to be drawn between two methods of determining exposure, i.e. the free-air and cavity ionization chambers. Secondly, because a large number of countries have had their secondary standards calibrated by one or other of the centres reporting this intercomparison. For instance, DAW cavity chambers have been used to calibrate commercial chambers of Czechoslovakian, Hungarian and Bulgarian institutions as secondary standards, because these countries still lack the facilities for absolute measurements (Table 1). Furthermore, NPL standard chambers have been compared with primary standard chambers of the NBS Washington (WYCKOFF et coll. 1963); NBS have calibrated a Swedish secondary standard and so on. So these comparisons will give some idea of the accuracy of the roentgen unit as used in a larger number of countries.

Ionization chambers for the absolute determination of exposure

The cavity ionization chambers of the Institute of Biophysics of DAW Berlin-Buch. The realization of the unit of exposure in the Institute of Biophysics of DAW is accomplished with a number of graphite cavity chambers with effective

Table 2

Details of the two DAW-chambers used for the intercomparisons

Chamber	C 1.5 No. 2	H III/1.5 No. 1
Measuring volume	1.507 cm^3	About 1.5 cm^3
Material	Graphite	Air-equivalent material
Wall thickness	3.4 mm = 580 mg/cm^2	3.4 mm = 590 mg/cm^2
Chamber voltage	400 V	400 V
Sensitivity according to DAW calibration at t = 22° C, p = 760 mm Hg, RH = 0 %, complete saturation	4.60×10^{-10} C/R	4.91×10^{-10} C/R

Table 3

Correction factors for the DAW cavity chamber C 1.5 No. 2 under different conditions of irradiation

		Corrections for the conditions of irradiation at		
		DAW	NPL	VNIIM
K_{Br}	Stopping power	1.004	1.004	1.004
K_{Sch}	Attenuation by total wall thickness	1.015	1.015	1.015
K_U^{Sch}	Irregularity of the intensity by attenuation	0.997	0.997	0.997
K_U^S	Irregularity of the intensity by geometry	0.995	0.999	0.995 (SCD = 60 cm)
K_{St}	Stem scatter	0.997	0.997	0.997
K_S	Saturation	1.003	1.001	1.000
Total	correction factor	1.011	1.013	1.008 ± 0.010

Maximum uncertainty of absolute exposure determination $\pm$ 2 %

volumes of from 1 cm^3 to 2 cm^3, the design of which has already been described (RAKOW & WILL 1963). The wall thickness of the chambers is varied by adding or removing close-fitting graphite caps; for ^{60}Co γ-radiation the thickness is 580 mg/cm^2. During measurement the chambers are connected via a co-axial cable to an electrometric photocell compensator (Townsend compensator), whose measuring capacitor, as well as the precision voltmeter, and the thermometer and barometer for air density determination, have been calibrated by the DAMW (DAMW = Deutsches Amt für Meßwesen und Warenprüfung). The chamber polarizing potential is 400 V. The constancy of chamber sensitivity is checked by a ^{90}Sr check source, in which the constant location of the chambers is ensured by means of plastic inserts so that a reproducibility of the control readings within ± 0.1 per cent is attained. The ionization measured per unit mass of dry air was corrected by a correction factor of the form

$$K = K_{Br} \cdot K_{Sch} \cdot K_U \cdot K_{St} \cdot K_S$$

where

K_{Br} = correction factor for the different electron stopping power of the chamber wall material and air
K_{Sch} = correction factor to take into account the attenuation of the primary radiation in the chamber wall
K_U = correction factor to take into account the non-uniformity of the primary radiation intensity over the active chamber volume through wall attenuation and through geometric attenuation
K_{St} = correction factor to take into account scatter from the chamber stem
K_S = correction factor for extrapolation to complete saturation.

These corrections so far have been determined for the experimental conditions existing at DAW Berlin-Buch (Rakow & Will 1963). For the conditions at NPL Teddington and VNIIM Leningrad some of the corrections could be determined directly by experiment and the shift of the remaining corrections could be estimated.

The comparisons were carried out with one of the DAW graphite cavity chambers which permits absolute measurements of the exposure, and with a secondary standard chamber of air-equivalent material (Will & Rakow 1970). Table 2 gives data of interest about these chambers. Table 3 contains corrections introduced into the measuring values of the graphite chamber under various conditions of irradiation.

Cavity ionization chambers of the NPL Teddington. The primary standard in the U. K. for exposure measurements with 2 MV roentgen rays is based upon three cylindrical graphite cavity chambers of nominal volume 2 cm^3 (Barnard, Axton, Belcher & Marsh 1956). The chambers are mounted integrally on duralumin stems permanently connected to lengths of non-microphonic co-axial screened cable. The polarizing potential applied to these chambers is 300 V, and their wall thickness is 500 mg/cm^2.

The chambers in turn are connected to one of a pair of Townsend balancing and measuring systems incorporating an electrometer triode valve bridge and standard capacitor. A whole-beam parallel plate monitor chamber is permanently connected to the other system.

Table 4

Correction factors for the NPL 2 cm³ standard graphite cavity chambers for 2 MV roentgen rays

$\dfrac{(m^{\mu}en)_{air}}{(m^{\mu}en)_{carbon}}$	0.999
$S_{m\ air}^{\ carbon}$	1.003
f_w	1.018
f_e	1.002
f^{+}	1.000
Total correction factor	1.022 ± 0.008

Maximum uncertainty of absolute exposure determination ± 1.5 %
[+]For the NPL calibration service the value of f is taken as 1.008 in order to retain a total correction factor of 1.03 as discussed on p. 148.

An exposure measurement in roentgens by the NPL chambers is given by

$$I \cdot \left[\frac{(m^{\mu}en)_{air}}{(m^{\mu}en)_{carbon}} S_{m\ air}^{\ carbon} \cdot f_w \cdot f_e \cdot f \right]$$

I = charge in coulombs collected per 2.58×10^{-4} kg of dry air

$\dfrac{(m^{\mu}en)_{air}}{(m^{\mu}en)_{carbon}}$ = ratio of the mass energy absorption coefficients

$S_{m\ air}^{\ carbon}$ = stopping power ratio carbon to air including polarization effect

f_w = correction factor to take into account the attenuation due to the presence of the chamber wall

f_e = correction factor to take into account lack of electronic equilibrium

f = composite correction factor to take into account lack of saturation, configuration factors and stem scatter contribution etc.

When the NPL initiated their 2 MV calibration service in 1956, the overall correction factor (the value of the expression in square brackets) was taken to be 1.03. However, by the year 1959 evidence had accumulated that this was probably an overestimate, possibly by as much as 1 per cent (BARNARD & MARSH 1959, BARNARD, MARSH & HITCHMAN 1964). Nevertheless, the value 1.03 has so far been retained for routine calibrations in the interests of consistency, bearing in mind that it still lies within the limits of uncertainty associated with the value now thought to be more nearly correct. There is no reason however, why, in international comparisons, a more recent estimate should not be taken, and therefore a value 1.022 has been used in the comparisons now reported. This is close to the value 1.020 used in an international comparison in 1961 (ICRU 1964).

Estimates of the individual factors are given in Table 4. For the last correction factor f, mutually compensating terms are thought to make its most likely value 1.000, but this factor has the greatest degree of uncertainty associated with it. The present estimate of the limits of uncertainty in the overall correction factor 1.022 is $\pm$ 0.008. The NPL wish to point out that they are at present reviewing the values of these factors and intend to publish new estimates when the work has been completed.

High-pressure standard ionization chamber of the Mendeleeff Institute for Metrology (Leningrad). The primary standard of the U. S. S. R. for the energy range from 0.3 MeV to 3 MeV is a parallel plate high-pressure ionization chamber with aluminium strips as potential guides. The high-voltage plate is 75 cm long, the collecting electrode 25 cm long and the two guard electrodes each 30 cm long. All electrodes are 40 cm wide, and the plate separation is 40 cm. The beam entrance window consists of 5.77 mm thick duralumin. The design of the chambers was described by AGLINTSEV et coll. (1961). The air pressure within the chamber may rise to a maximum of 20 atmospheres and the chamber voltage to as high as 15 kV. The ionization current is measured by Townsend compensator.

Ionization measured per unit mass of air is corrected by the following factor

$$K = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6$$

where

K_1 = correction for radiation attenuation in the inlet window of the tank
K_2 = correction for radiation attenuation by air layer between the inlet window of the tank and the centre of the measuring electrode
K_3 = correction for absence of saturation conditions in the standard chamber
K_4 = correction for penetration of radiation through the diaphragm edges
K_5 = correction for displacement of the effective region of gamma radiation absorption relative to the measuring volume
K_6 = correction for influence of the scattering radiation in air.

The magnitudes of the individual factors are listed in Table 5.

Sources of radiation

The ^{60}Co teletherapy unit of DAW Berlin-Buch. The measurements in Berlin-Buch were carried out on the Theratron Junior ^{60}Co irradiation unit of the

Table 5

*Correction factors introduced when measuring ^{60}Co exposure rate with the VNIIM standard device for 0.3 to 3 MeV**

K_1	1.085
K_2	1.074
K_3	1.073
K_4	0.950
K_5	0.992
K_6	0.988
Total correction factor	1.164 ± 0.013

Maximum uncertainty of absolute exposure determination ± 1.5 %
*Conditions: chamber air pressure 10 atm, temperature 20 °C, chamber field strength 440 V/cm.

Robert-Roessle-Clinic of the DAW. The measurements were made at the rotation centre of the unit (SCD 55 cm) to eliminate the distance error through irradiation with the two opposite positions of the source. The field size was 15 cm $\times$ $\times$ 15 cm at a distance of 55 cm, and the exposure rate under these conditions on 1 November 1966 was 55 R/min.

The 2 MV roentgen source of the NPL Teddington. The NPL uses a roentgen ray beam produced by a 2 MV Van de Graaff generator, having a tungsten transmission target and a focal spot of approximately 1 mm diameter. The diaphragm system was described by ASTON & SMITH (1954) and this produces a canalized beam, circular in cross-section. The broad spectrum of radiation can be represented by an equivalent spectrum with only three monoenergetic components (BARNARD et coll. 1959). More recently (BARNARD, MARSH & HITCHMAN 1964) good experimental agreement was reached with spectra calculated according to KRAMERS' method (1923).

For the measurements described in the paper, an aperture size was chosen so as to give a beam diameter of 4.5 cm at the calibration distance of 180 cm so that the ionization chambers were completely enveloped. The HVT of the roentgen beam was 12 mm Cu and the exposure rate at 180 cm was approximately 12 R/min.

^{60}Co radiation source of the primary standard of the VNIIM Leningrad. The ^{60}Co gamma emitter used for the comparison measurements in Leningrad with an activity of 4.5 Ci on 1 June 1966 (diameter 4 mm, height 4 mm, surrounded by a capsule of stainless steel of 1 mm wall thickness), is placed into a lead container of 35 cm diameter in a special holder. The diameter of the emerging beam

Table 6

Results of the comparison of the cavity ionization chambers of DAW and NPL

Chamber		C 1.5 No. 2	H III/1.5 No. 1
Sensitivity as determined by NPL (uncorrected) $C/R \times 10^{10}$	(a)*	4.639**	4.934
	(b)	4.640	4.935
	(c)	4.641	4.931
Mean		4.640	4.933
Sensitivity as determined by NPL (corrected) $C/R \times 10^{10}$		4.54	4.83
Sensitivity as determined by DAW (uncorrected) $C/R \times 10^{10}$		4.65	4.97
Sensitivity as determined by DAW (corrected by DAW for NPL conditions) $C/R \times 10^{10}$		4.59	4.90
Ratio of uncorrected sensitivities NPL/DAW		1.00	0.99
Ratio of corrected sensitivities NPL/DAW		0.99	0.99

*The comparison was carried out on three separate occasions.
**All sensitivities quoted are for dry air at 22 °C and 760 mm Hg.

Table 7

Results of the comparison of the cavity chambers of DAW with the high-pressure ionization chamber of VNIIM

Chamber		C 1.5 No. 2	H III/1.5 No. 1
Sensitivity as determined by VNIIM $C/R \times 10^{10}$	(a)*	4.54**	4.93
	(b)	4.49	4.87
	(c)	4.58	
	(d)	4.63	
Mean		4.56	4.90
Sensitivity as determined by DAW (corrected by DAW for VNIIM conditions) $C/R \times 10^{10}$		4.60	4.91
Ratio of sensitivities VNIIM/DAW		0.99	1.00

*The comparison was carried out on four separate occasions.
**All sensitivities quoted are for dry air at 22 °C and 760 mm Hg.

Table 8

Summary of international comparisons on DAW Chamber C 1.5 No. 2

Standardising laboratory	NPL		VNIIM	
Measurement or correction by	NPL	DAW	VNIIM	DAW
Mean uncorrected sensitivities $C/R \times 10^{10}$	4.64	4.65	5.31	4.64
Mean corrected sensitivities $C/R \times 10^{10}$	4.54	4.59	4.56	4.60

can be varied by using lead diaphragms of from 30 mm to 60 mm diameter at a distance of 15 cm from the source. Radiation scattered in the container and diaphragm with 30 or 60 mm diameter of the diaphragm is 2 or 4 %, respectively (Tucin et coll. 1965). The exposure rate at 50 cm distance was about 0.3 R/min on 1 June 1966.

Results of the intercomparisons

Comparisons with the cavity ionization chambers of the DAW and the NPL. Comparative measurements with the cavity ionization chambers of the two institutions were carried out at NPL during September 1965 and March 1967. The same charge measuring apparatus including standard capacitor was used for all chambers and the intercomparison was carried out via a whole-beam monitor chamber. All the chambers used in the experiments were unsealed, and, because it was assumed that all the chambers responded equally to changes in ambient air conditions, there was no need to apply any corrections for different ambient air conditions in the experiments. The cavity chambers of both institutions were of similar size so that no corrections for lack of beam uniformity were necessary.

From this intercomparison it appears that the ratio of the response of the DAW chamber C 1.5 No. 2 to the mean response of the NPL chambers is unity. For the air-equivalent chamber H III/1.5 No. 1 this ratio is 1.01. If the corrections to the chambers as determined by their owners are applied then the exposure as determined by NPL is 1 per cent greater than that determined by the DAW chambers. These results are listed in Table 6.

The deviations in determining exposure are thus attributable to the respective differing corrections that are used.

Comparison between the cavity ionization chambers of DAW and the high-pressure chamber of VNIIM. The comparison measurements were made in May 1966 at source-chamber distances of 60 cm and 80 cm and for diaphragm diameters of 30 and 60 mm (corresponding to field diameters of 120 and 240 mm at a distance of 60 cm). The results of the comparsion are presented in Table 7. The considerable scatter of the measured values is presumably due to the inaccuracy in determining the chamber-source distance at the time of that comparison. The results showed that the response of the DAW chambers obtained at the two institutes differed by not more than 1 per cent.

Conclusion

The final results of the comparisons between the primary ionization chambers of the three countries involved are summarized in Table 8. Using correction factors thought by the respective centres to be most appropriate, these results show agreement to about 1 per cent. This is within the estimated limits of accuracy claimed by each of the laboratories. It is reasonable to suppose therefore that the realization of the unit of exposure by means of high-pressure and cavity ionization chambers is accurate to within about 2 per cent. This provides confirmation of the validity of secondary-standard calibrations for other countries carried out by the three centres concerned in the present intercomparisons.

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The comparison carried out at the NPL was based upon the standards and corrections established principally by Dr G. P. Barnard to whom the authors would like to dedicate their contribution in memoriam.

SUMMARY

The primary standard cavity ionization chambers of DAW Berlin were compared with the primary standard high-pressure ionization chambers of VNIIM Leningrad using their ^{60}Co unit, and with the primary standard cavity ionization chambers of NPL Teddington using their 2 MV Van de Graaff roentgen ray generator. With correction factors thought by the respective centres to be most appropriate, the comparisons showed agreement to about one per cent, which is within the estimated limits of accuracy claimed.

ZUSAMMENFASSUNG

Hohlraumionisationskammern der DAW Berlin wurden mit der Primärstandard-Druckluft-Ionisationskammer des VNIIM Leningrad an einer ^{60}Co-Einheit und mit den Primärstandard-Ionisationskammern des NPL Teddington an dessen 2 MV Van de Graaff Generator verglichen. Unter Verwendung der von den entsprechenden Institutionen bestimmten Korrektionsfaktoren zeigen die Vergleiche Übereinstimmung auf etwa ein Prozent, was innerhalb der Fehlergrenzen liegt.

RÉSUMÉ

Les auteurs ont comparé les chambres d'ionisation à cavité étalons primaires de la DAW de Berlin avec les chambres d'ionisation étalons primaires à haute pression du VNIIM de Léningrad au moyen de leur unité à ^{60}Co et avec les chambres d'ionisation à cavité étalons primaires du NPL de Teddington au moyen de leur générateur de rayon de roentgen de Van de Graaff à 2 MV. En tenant compte des facteurs de correction considérés comme les meilleurs par les différents centres ces comparaisons ont montré une concordance à environ un pour cent près, ce qui est dans les limites de précision attendue.

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