

Practical Session in kV X-Ray Dosimetry

Brief History

From the early 1900's NPL responded to the requests of British radiotherapists to calibrate the dosimeters they used for standardising the dose delivered to patients. From the beginning, the particular kVs chosen to generate X-ray beams at NPL were intended to match those used in clinical radiotherapy. In 1971 it was decided to derive a new range of X-ray qualities. For many years hospital physicists had been using half-value layer (HVL) to specify the beam qualities for kV energy X-ray beams in terms of HVL in aluminium up to 4 mm Al HVL (about 100 kV), and in terms of copper for the higher energy X-ray beams up to 4 mm Cu HVL (about 300 kV). A total of eighteen X-ray qualities (see Appendix 1) were chosen, at standardised values of HVLs spaced as evenly as possible, so that it would be easy for users to interpolate between them.

Two primary standard parallel plate free-air chambers are maintained by the National Physical Laboratory for the realisation of air kerma (kinetic energy relaxed per unit mass) in terms of the base units, i.e. $1 \text{ Gy} = 1 \text{ J kg}^{-1}$. These primary standards are designed to measure X-rays generated at between 8 kV and 50 kV and between 40 kV and 300 kV.

In the UK traditionally about 30 secondary standard centres across the UK (university and teaching hospitals), send their secondary standards to NPL for calibration against the primary standard every three years. Smaller hospitals will send their tertiary standards to the secondary standard centres to get them calibrated against the secondary standards. Field instruments, used for daily routine measurements, will be calibrated in hospitals about once every year against either secondary or tertiary standards. However, nowadays NPL will calibrate any dosemeter that is of secondary standard quality.

Realisation of Air Kerma (from first principles)

Air kerma K is the quantity realised by the **free-air chamber** and is defined¹ as "The quotient of dE_{tr} by dm where dE_{tr} is the sum of the initial kinetic energies of all the charged ionising particles liberated by uncharged ionising particles in air of mass dm ",

$$K = \frac{dE_{tr}}{dm} \quad (1)$$

Applying the definition of air kerma to a free-air chamber we obtain Equation 2,

$$K = \frac{Q}{m} \frac{W_{air}}{e} \frac{F}{(1-g)} \quad (2)$$

where

Q	is the measured charge,
m	is the mass of air in the collecting volume,
W_{air}/e	is the energy required to produce an ion pair in dry air ² (= 33.97 J/C),
F	is the total correction factor applied to the free-air chamber and
g	is the fraction of ionisation due to bremsstrahlung ² (this is equal to zero for kV X-rays, i.e. energies between 8 keV and 300 keV mentioned in this practical session).

Figure 1 shows a schematic diagram of a free-air chamber. A mono-directional beam of X-rays passes through a defining aperture of accurately known area, A , enters a metal box and passes out through a hole on the far side of the box without striking anything in the box other than the air it contains. This fulfils the requirement that the X-rays interact only with air.

The separation of the electrodes in the chamber and its other dimensions are such that electrons released in the collecting volume lose all their energy before they can reach the electrodes or chamber walls. This ensures that the electrons are completely stopped by air. A high potential difference (field strength of the order of 100 V/cm) maintained between the high-voltage electrode and the collecting electrode of length L sweeps the ions of one sign produced between the dotted lines (see Figure 1) to the collecting electrode. The effective length, L_{eff} , of the collecting electrode is the actual length of the collecting electrode L plus half the width of the two gaps to the adjacent earthed guard electrodes. A system of guard bars, to which graded electrical potentials are applied, together with the guard electrodes, ensures that the field lines between the collecting electrode and the high voltage electrode are straight and perpendicular to those electrodes.

The ions are therefore collected from a defined volume and the charge Q is measured. The collecting volume is defined by the aperture area, A , and the effective length, L_{eff} , of the collecting electrode (along the X-ray beam axis). The actual collecting volume (see Figure 1, dark grey area) varies with the distance between the free-air chamber and the focal spot of the X-ray tube. Because of the difficulty of measuring the actual collecting volume the defining plane is moved from the centre of the collecting electrode to the front face aperture. The volume then becomes AL_{eff} , and the mass of air within this volume is $m = AL_{eff}\rho$, where ρ is the air density^{3,4} at a pressure of 1013.25 mbar, a temperature of 20°C and 50% relative humidity.

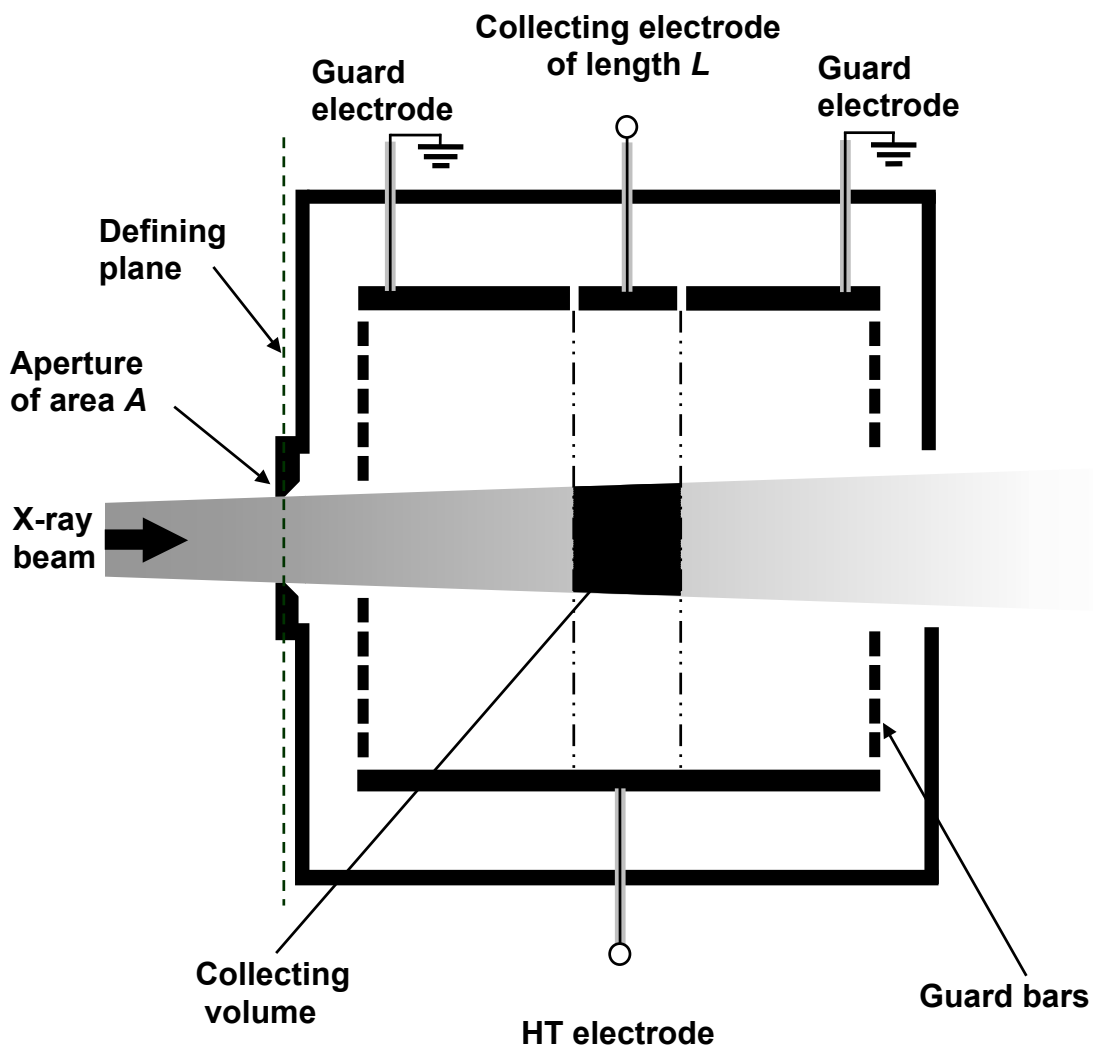


Figure 1 Schematic diagram of the NPL primary standard free-air ionisation chamber

The Free-Air Chamber Correction Factors

The total correction factor (F) (see Equation 2) is the product of several correction factors, which are listed below.

Some of the ions, which are produced in the collecting volume of the free-air chamber, are lost by ion **recombination** before they reach the collecting electrode and it is necessary to determine this correction.

Correction for the **air attenuation** between the aperture and the collecting electrode is necessary because the reference point of the chamber is taken to be the defining plane of the aperture and not the centre of the collector.

A **field distortion** correction is necessary because the electric field inside the free-air chamber is not perfectly perpendicular to the electrodes at all points. This is despite the presence of the guard bars, which only reduce the distortion effect.

Correction for the **front face penetration** is necessary if the front face of the free-air chamber is not thick enough to attenuate the X-ray beam. It is more important with large beam sizes and high energy beams.

An **HT polarity** correction is necessary because the measured charge can depend on the polarity of the HT supply. The potential is negative for routine measurements. A correction of half the difference between measurements with positive and negative polarity is applied.

A correction has to be made for photons which are scattered from the main beam through the chamber and which produce ionisation in the space between the electrodes not defined by the ionisation volume. This was measured by surrounding the X-ray beam through the chamber as closely as possible with a plastic cone of sufficient thickness to stop the secondary electrons produced by interactions in the collecting volume. This allows the **scattered photons** to pass with minimum attenuation and the contribution of these photons to the total ionisation can therefore be measured.

An **ion loss** correction is necessary at higher energies when the plate separation is less than the range of the secondary electrons in air. It has been calculated using Monte Carlo techniques.

A correction for **humidity** is applied in accordance with the recommendation of CCEMRI⁵.

How a Customer's Chamber is Calibrated at NPL

A transmission monitor chamber is used to correct all measurements for any variations in X-ray tube output. At the beginning of each measuring cycle (electrometer unearthed, shutter closed) a pre-exposure leakage current is measured for typically 15 s. Then the shutter opens and the ionisation current will be measured for an exposure time of, say, 30 s. The shutter closes, however, the electrometer stays unearthed. Finally, the post-exposure leakage current is measured for another 15 s, after which the electrometer will be earthed for the next measuring cycle.

- a) At the beginning, the ionisation current will be measured using the primary standard.
- b) Next, the secondary standard will be moved into the X-ray beam (same position as the primary standard) to measure the ionisation current.

- c) Finally, another primary standard measurement will be carried out.
- d) Now the mean ionisation current for the primary standard can be determined and a temperature corrected standard to monitor response can be calculated.
- e) A temperature corrected standard to monitor response can also be calculated for the secondary standard.
- f) The air kerma sensitivity (in terms of Gy/C) of the secondary standard is the ratio of the primary standard response to the secondary response multiplied by the primary standard sensitivity (in terms of Gy/C) for the particular X-ray quality used during the calibration.

A typical calibration curve for a NE 2561 chamber is shown in Figure 2.

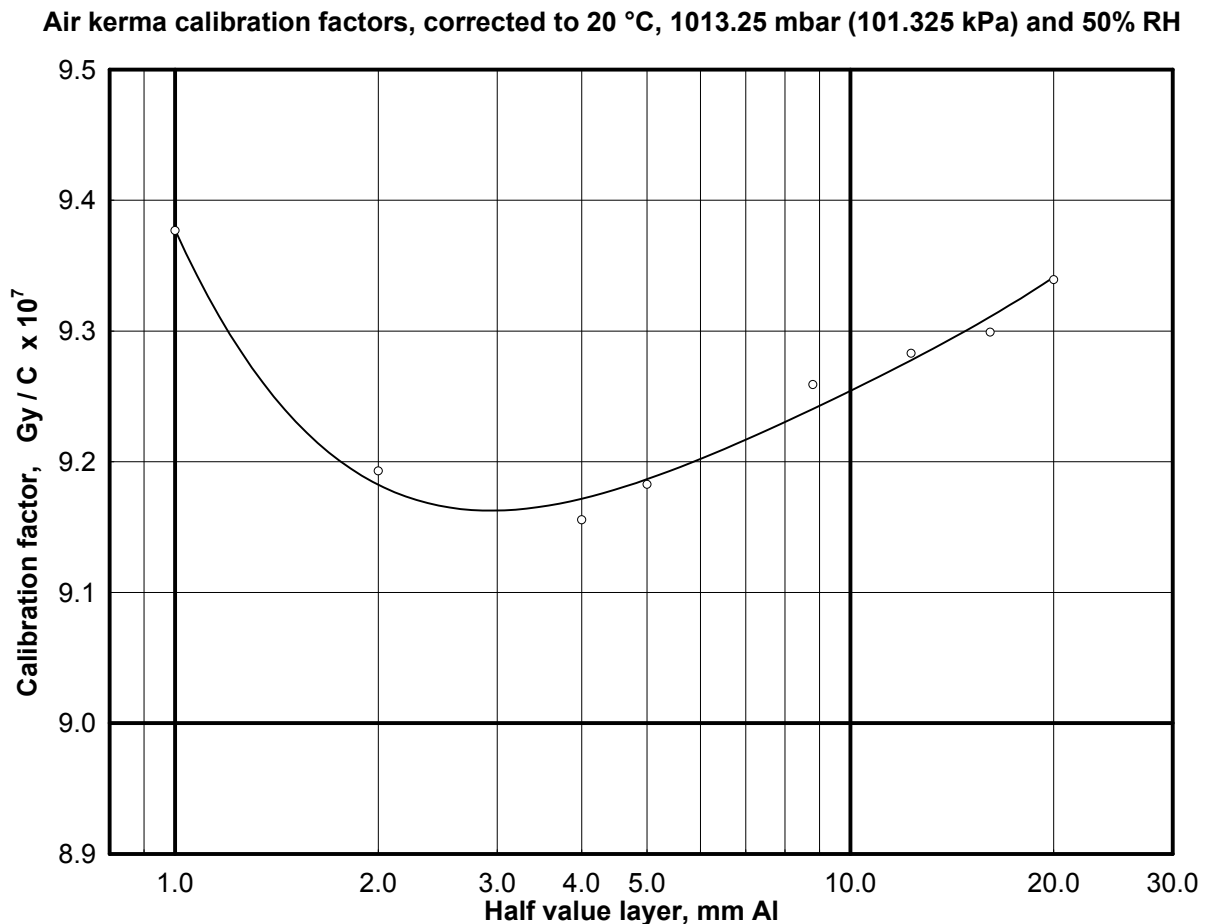


Figure 2 A typical calibration curve for a NE 2561 ionisation chamber

References

1. ICRU(1980); International Commission on Radiological Units and Measurement, Radiation Quantities and Units. *ICRU Report 33*.
2. CCEMRI 1985 report of the 8th meeting of section I (Rayons X et γ , électrons). *Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants, Rapport de la 11^{ème} session* (Sèvres: BIPM) R157-166.
3. Giacomo, P; Equation for the determination of the Density of Moist Air (1981). *Metrologia* **18**, 33-40, (1982)
4. Davis, R S; Equation for the determination of the density of moist air (1981/91). *Metrologia* **29**, 67-70, (1992)
5. Correction d'Humidité Report of the 4th meeting of Section I (Rayons X et γ , électrons). *Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants, Rapport de la 4^{ème} Réunion - 1977* page R(I)6. Bureau International des Poids et Mesures (BIPM), Sèvres, 1977.

APPENDIX 1

X-ray qualities used for therapy-level exposure and air kerma calibrations at NPL

Quality	Half-value layer	Generating potential	Added filter	Approximate air kerma rate
Reference number	mm Al	kV	mm Al	Gy/min
2.4.1	0.024	8.5	None	0.08
2.4.2	0.036	10	0.025	0.13
2.4.3	0.050	11.5	0.050	0.17
2.4.4	0.070	14	0.11	0.18
2.4.5	0.10	16	0.20	0.18
2.4.6	0.15	20	0.30	0.22
2.4.7	0.25	24	0.45	0.21
2.4.8	0.35	34	0.47	0.39
2.4.9	0.50	41	0.56	0.43
2.4.10	0.70	44	0.74	0.40
2.4.11	1.00	50	1.01	0.33

Table A1.1 Therapy-level very-low energy X-rays, 0.035-1.0 mm Al HVL.
Thin-window ionisation chambers (PTW 23344 and PTW 23342)
Inherent filtration 1 mm Be
Focus-chamber distance 0.5 m

Quality	Half-value layer		Generating potential kV	Added filtration	
	mm Al	mm Cu		mm Cu	mm Al
2.2.1	1.0	0.030	50		0.75
2.2.2	2.0	0.062	70		1.6
2.2.3	4.0	0.150	100		3.4
2.2.4	5.0	0.200	105	0.1	1.0

Table A1.2 Therapy-level low energy X-rays, 1.0-8 mm Al HVL.
 Secondary standard thimble chamber
 Inherent filtration 2.5 mm Be + 4.8 mm Perspex
 Focus-chamber distance 0.75 m

Quality	Half-value layer		Generating potential kV	Added filtration		
	mm Al	mm Cu		mm Sn	mm Cu	mm Al
(a) Inherent filtration 2.5 mm Be + 4.8 mm Perspex						
2.2.5	8.8	0.50	135		0.27	1.0
(b) Inherent filtration 4 mm Al equivalent + 4.8 mm Perspex						
2.2.6	12.3	1.0	180		0.42	1.0
2.2.7	16.1	2.0	220		1.20	1.0
2.2.8	20.0	4.0	280	1.4	0.25	1.0

Table A1.3 Therapy-level medium energy X-rays, 0.5-4 mm Cu HVL.
 Secondary standard thimble chamber
 Focus-chamber distance 0.75 m

APPENDIX 2

Definitions used in this section of the course

Primary standard: An instrument of the highest metrological quality that permits determination of the unit of a quantity from its definition, and the accuracy of which has been verified by comparison with the comparable standards of other institutions participating in the international measurement system. A primary standard is usually a one-off instrument. Our primary standard was designed by the NPL workshop in consultation with the physicists.

Secondary standard: An instrument of secondary standard quality that has been calibrated by comparison with a primary standard.

Temperature and Pressure correction factor: The calibration factors reported in the NPL certificate apply when the chamber is used in ambient atmospheric conditions of 20 °C, 1013.25 mbar (101.325 kPa) and 50% relative humidity (standard conditions). For accurate measurements it is therefore necessary to correct ($k_{T,P}$) for any differences between the air density in the chamber at the time of measurement and that for which the calibration factor applies using:

$$k_{T,P} = \frac{(273.15 + T)}{293.15} \cdot \frac{1013.25}{P} \quad (3)$$

Where:

T is the ambient temperature in °C and
 P is the ambient atmospheric pressure in mbar.

Tertiary standard: An instrument calibrated by direct comparison with a secondary standard.

Field instrument: A measuring instrument used for routine measurements (i.e. in an X-ray department to measure the output of the X-ray tubes on a daily basis).

Standard deviation of the mean (SDOM):

$$SDOM [\%] = \frac{\sigma_{n-1}}{\bar{x} \times \sqrt{n}} \times 100$$

Where:

σ_{n-1} is the standard deviation of n readings,
 \bar{x} is the mean of n readings and
 n is the number of readings.