

Dosimetry and calibration of photon and electron beams with cavity ion chambers

AAPM Task Group 51

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Introduction

- Calibration of ion chambers
 - Exposure calibrations
 - Exposure
 - N_{gas}
 - Absorbed dose calibrations
 - N_D
- Calibration of photon beams
 - In free space dosimetry
 - Phantom dosimetry

Absolute cavity ion chambers

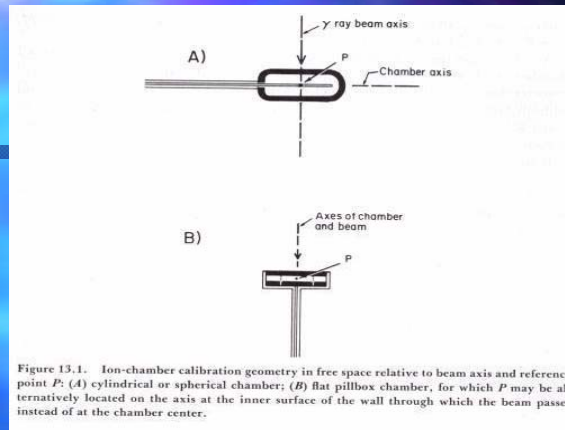
- The volume has to be known with accuracy, most suited for large volumes
- Ionization chambers used in most dosimetric applications are manufactured commercially and need to be calibrated by one of the methods described
- For an absolute cavity chamber,
$$N_{\text{gas}} = (W/e) \text{ mg}^{-1}$$

Calibration of ion chambers using x- or gamma-rays

- NIST maintain standard ionization chambers and calibrated gamma-ray beams
- ADCL (Accredited Dosimetry Calibration Laboratory) are regional calibration labs linked to the NBS with frequent calibrations of high quality ion chambers.
- There is a fee for calibration in either lab

Exposure calibration of ion chambers

- With x-rays generated at 10-300 kV
 - Chamber wall requirements. The wall must be made thick enough to provide CPE and keep out stray electrons. For a 300 kV beam that will produce a maximum electron energy of 300 keV about 0.8 mm of polystyrene is required.
 - For low energies such as used in mammography, a thinner wall thickness is indicated. For a 50 keV electron, the CSDA range in polystyrene is 42 μm .



$$N_x = \frac{X}{M}$$

R/C
R/scale division

Reading corrected for standard TP

Exposure calibrations of ion chambers with ¹³⁷Cs and ⁶⁰Co gamma-rays

- The same procedure is used for exposure calibration of cavity chambers for x-rays < 300 kV, except that the free-air chamber is replaced by the absolute graphite cavity chamber as a standard. In that case, a buildup cap is necessary to keep CPE and stray electrons out.

Ngas calibration of ion chambers

- One useful mode of calibrating dosimeter is in terms of the absorbed dose in the matter of the sensitive volume of the dosimeter.
- This can be related to the dose in another medium that replaces the dosimeter in the same location, by an application of cavity theory.
- This applies well to gas in cavity ion chambers. The calibration can be done for all ionization radiation for which W/e is constant.

Loevinger's formalism (AAPM TG21, 1981)

$$N_{\text{gas}} = \frac{D_{\text{gas}} A_{\text{ion}}}{M}$$

For an absolute cavity chamber

$$N_{\text{gas}} = \frac{1}{m_g} \left(\frac{\overline{W}}{e} \right)_g \quad (\text{Gy/C})$$

Attix derivation of N_{gas} from X

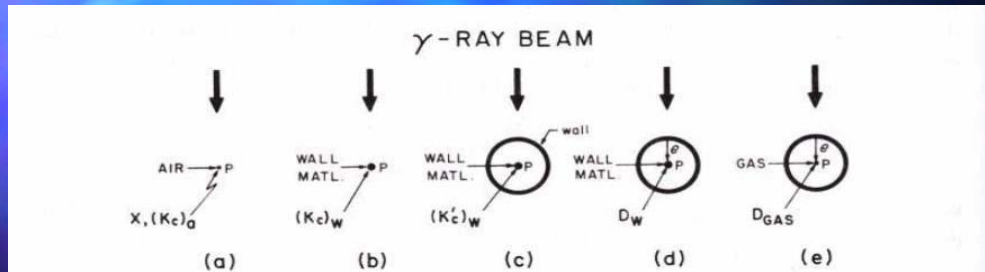
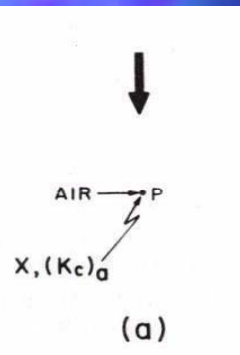
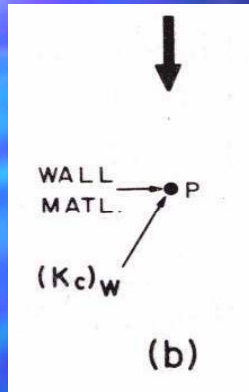


Figure 13.2. The relation of D_{gas} to the free-space exposure X in a γ -ray calibration. Identical incident irradiations are assumed in each case. (a) Exposure at point P in free space is X ; $(K_c)_a = X(\overline{W}/e)_a$. (b) The collision kerma in an imaginary infinitesimal mass of wall material placed at P is $(K_c)_w = (K_c)_a(\mu_{en}/\rho)_w^a$. (c) The chamber is centered at P ; wall attenuation reduces $(K_c)_w$ to $(K_c')_w = A_w(K_c)_w$. (d) The absorbed dose in the bit of wall material at P is $D_w = (K_c')_w(1 + \mu'x)$, delivered by electrons coming mostly out of the front wall. (e) The bit of wall material is removed from P ; the dose in the cavity gas there is $D_{\text{gas}} = D_w(\overline{L}/\rho)_{w,g}^e$. After Attix (1984b). Reproduced with permission from the American Institute of Physics.



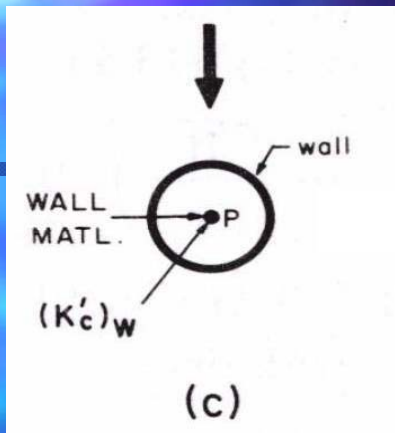
The collision kerma (J/kg) in air at the calibration point P in free space (see Fig. 13.2a) is related to X by

$$(K_c)_a = X \left(\frac{\overline{W}}{e} \right)_a \quad (13.3)$$



Imagining now an infinitesimal bit of the chamber's wall material w to be positioned at P in free space (see Fig. 13.2b), the collision kerma in it can be related to $(K_c)_a$ by

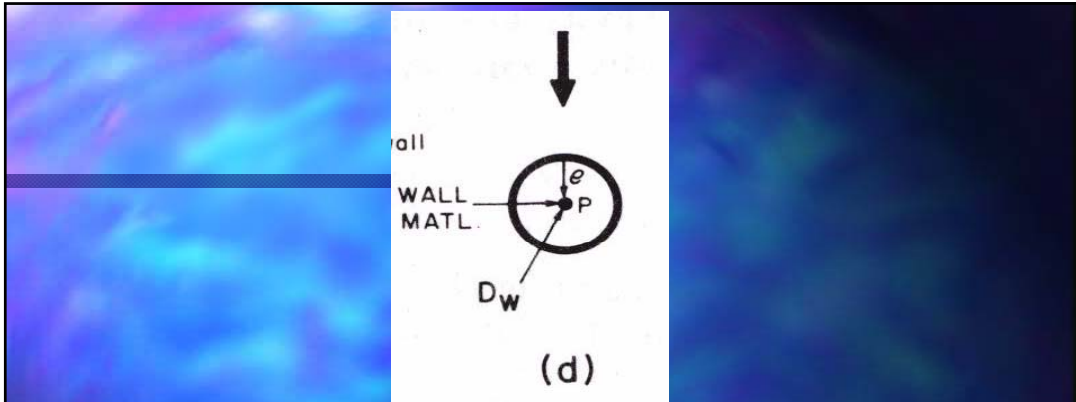
$$(K_c)_w = (K_c)_a \left(\frac{\mu_{en}}{\rho} \right)_a^w \quad (13.4)$$



Now positioning the chamber with its center at P as in Fig. 15.2c, the broad-beam attenuation of the γ -rays in the wall reduces the collision kerma in the bit of wall material at P to

$$(K'_c)_w = A_w (K_c)_w \quad (13.5)$$

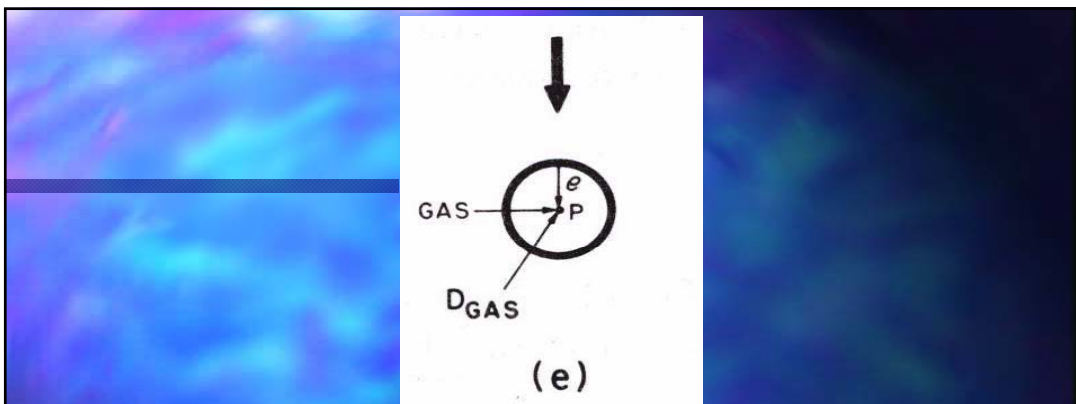
$$A_w = e^{-(\mu'/\rho)_w \rho t} \cong 1 - \left(\frac{\mu'}{\rho} \right)_w \rho t \cong 1 - \left(\frac{\mu_{en}}{\rho} \right)_w \rho t$$



The absorbed dose D_w in the imaginary bit of wall material at P is deposited by electrons that originate from Compton interactions in the chamber wall, mainly on the “upstream” side as indicated schematically in Fig. 13.2d.

Assuming TCPE to exist in the wall w , since w is thicker than the maximum electron range

$$D_w = \left(1 + \rho \bar{x} \frac{\mu'}{\rho} \right)_w (K'_c)_w \equiv \beta_w (K'_c)_w$$



If now the bit of wall material is removed from P , letting the cavity gas replace it, one can calculate the absorbed dose in that gas from cavity theory. The electron fluence coming from the wall will be unchanged; thus the dose at P will be approximately proportional to the mass collision stopping power of the material occupying that position, according to B-G theory.

$$D_{\text{gas}} = D_w \left(\bar{L} / \rho \right)_w^g$$

← Spencer - Attix

Finally, we may combine the results of Eqs. (13.3) through (13.8) to obtain

$$D_{\text{gas}} = X \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_a^w A_w \beta_w \left(\frac{\overline{L}}{\rho} \right)_w^g \quad (13.9)$$

which can be substituted into Eq. (13.2) to give

$$N_{\text{gas}} = \frac{X(\overline{W}/e)_a (\overline{\mu_{\text{en}}}/\rho)_a^w A_{\text{ion}} A_w \beta_w (\overline{L}/\rho)_w^g}{M} \quad (13.10)$$

Making use of Eq. (13.1) then produces the following relationship between N_{gas} (in Gy/C) and N_X (in kg^{-1}):

$$N_{\text{gas}} = N_X \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_a^w A_{\text{ion}} A_w \beta_w \left(\frac{\overline{L}}{\rho} \right)_w^g \quad (13.11)$$

For the case where the chamber wall is enclosed within an equilibrium buildup cap of a different material (a complication to be avoided where possible) the AAPM (1983) protocol recommends that Eq. (13.11) be replaced by a semiempirical expression due to Almond and Svensson (1977):

$$N_{\text{gas}} = N_X \frac{(\overline{W}/e)_a A_{\text{ion}} A_w \beta_w}{\alpha (\overline{L}/\rho)_g^w (\overline{\mu_{\text{en}}}/\rho)_w^a + (1 - \alpha) (\overline{L}/\rho)_g^{\text{cap}} (\overline{\mu_{\text{en}}}/\rho)_{\text{cap}}^a} \quad (13.11a)$$

in which “cap” refers to the buildup cap material, α is the fraction of ionization due to electrons from the chamber wall, and $1 - \alpha$ is the fraction due to electrons from the cap, as given in Fig. 13.7a (Section V.B below).

Calibration of ion chambers in terms of absorbed dose in water

- Current AAPM protocol (TG51) uses this method

$$N_D = \frac{D_{\text{wat}}}{M}$$

$$N_{\text{gas}} = \frac{D_{\text{gas}} A_{\text{ion}}}{M} = \frac{(\bar{L}/\rho)_w^g \beta_w A_{\text{ion}} (\overline{\mu_{\text{en}}/\rho})_{\text{wat}}^w D_{\text{wat}}}{P_{\text{repl}} \beta_{\text{wat}} M}$$

$$N_{\text{gas}} = \frac{N_D A_{\text{ion}}}{P_{\text{repl}}} \left(\frac{\bar{L}}{\rho} \right)_w^g \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_{\text{wat}}^w$$

Calibration of photon beams with an exposure-calibrated ion chamber

Calibrations in free space

- For x-rays generated at 10-300 kV

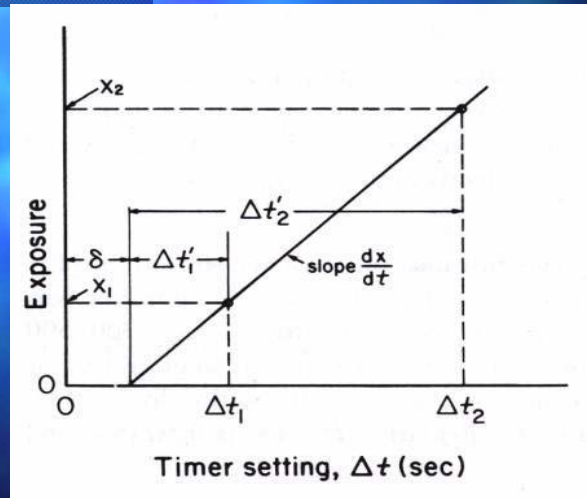
The ion chamber has N_x determined for the quality of the radiation to be measured.

$$X = N_x M$$

If recombination is to be taken into account

$$X = N_x A_{\text{ion}} M P_{\text{ion}}$$

Shutter timer error



Beam calibration in terms of free-space collision kerma or absorbed dose

Following the same scheme for the Ngas derivation

The free-space K_c in air at P for an exposure X is

$$(K_c)_a = X \left(\frac{\overline{W}}{e} \right)_a$$

The K_c in an infinitesimal mass of any other material x placed at P and similarly irradiated is

$$(K_c)_x = (K_c)_a \left(\frac{\mu_{en}}{\rho} \right)_a^x$$

The D at P is in general indeterminate without knowing the secondary flux-density distribution.

However, under CPE conditions we can write $D=Kc$ without further knowledge of the electron field.

By centering the spherical mass of material x at the point P and making the sphere's radius equal to the maximum secondary-electron range, CPE can be approximated.

Taking x to be water and assuming only Compton interactions for a 300 kV photons, the maximum recoil electron energy will be 162 kV, for which the CSDA range is about 0.32 mm.

$$(K_c)'_{\text{wat}} = A_{\text{eq}} (K_c)_{\text{wat}}$$

$$A_{\text{eq}} \cong 1 - \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_{\text{wat}} (\rho t)_{\text{wat}}$$

$$= 1 - (0.03 \text{ cm}^2/\text{g})(0.032 \text{ g/cm}^2) = 0.999$$

$$D_{\text{wat}}^{\text{CPE}} = (K_c')_{\text{wat}} = A_{\text{eq}}(K_c)_{\text{wat}} = A_{\text{eq}} X \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_a^{\text{wat}}$$

$$D_{\text{wat}}^{\text{CPE}} = 0.876 A_{\text{eq}} X \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_a^{\text{wat}}$$

Absorbed dose to water in free space

Free-space photon beam exposure calibration for energies above 300 keV

a. ^{60}Co and ^{137}Cs gamma-rays

^{137}Cs gamma-rays are seldom used any longer for calibration purposes.

$$D_{\text{wat}}^{\text{CPE}} = 0.876 A_{\text{eq}} X \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_{\text{a}}^{\text{wat}}$$

Insert β_{wat}

b. Higher Energy Photons

Calibration laboratories do not offer a calibration factor for higher energy photon beams above ^{60}Co energy.

It is possible to deduce a value of N_X for a higher energy beam through the double application of N_{gas} equation.

the trick here is to use a buildup cap equal to at least the maximum range of electrons produced by the higher energy photons.

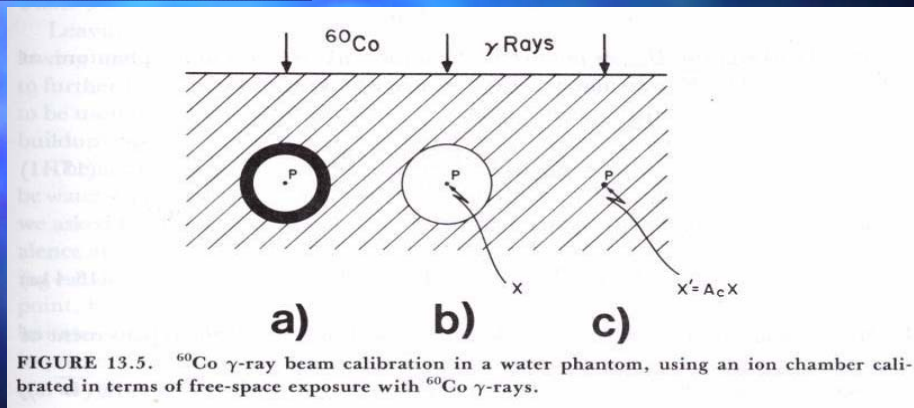
$$(N_X)_\lambda = (N_X)_{\text{Co}} \frac{[(\overline{\mu_{\text{en}}}/\rho)_a^w A_{\text{ion}} A_w \beta_w (\overline{L}/\rho)_w^g]_{\text{Co}}}{[(\overline{\mu_{\text{en}}}/\rho)_a^w A_{\text{ion}} A_w \beta_w (\overline{L}/\rho)_w^g]_\lambda}$$

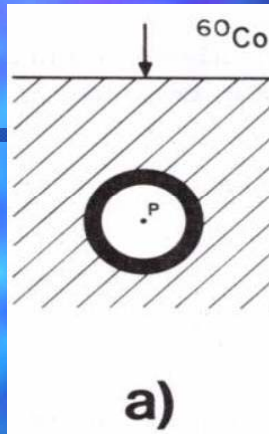
The problem is the availability of β_w for the higher photon energies.

Calibration of photon beams in phantom by means of an exposure-calibrated ion chamber

This has been used for many years before TG 21 came along. For higher energies than ^{60}Co gamma-rays the imaginary sphere of water around the point of measurement tends to become larger and the meaning of absorbed dose in free space starts to lose its meaning. Since the absorbed dose in a water phantom is what is wanted it may be more interesting to calibrate the beam in a point in such a water phantom and relate the absorbed dose there to doses at other points in the phantom. This reference point has to be deep enough in the phantom to achieve TCPE.

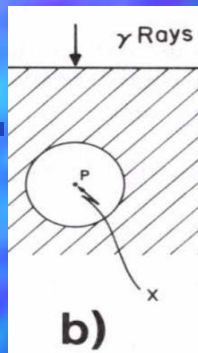
For ^{60}Co gamma-rays



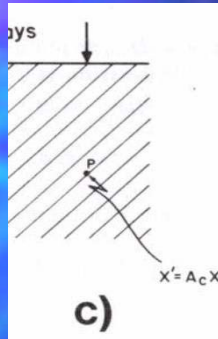


$$X = N_X A_{\text{ion}} MP_{\text{ion}}$$

What is the meaning of X within a phantom?



Now the ion chamber is removed and at the point P we have measured X. The response of the ion chamber has to be **air equivalent** within the energy range (from ^{60}Co gamma-ray energy downward the response of the ion chamber has to be constant per roentgen for the scattered photons.



$$X' = A_c X$$

A_c is the displacement correction, it is the fraction by which the exposure is decreased by broad-beam attenuation in the water occupying the former empty space.

$$(K_c)_a = X' \left(\frac{\overline{W}}{e} \right)_a$$

$$(K_c)_{\text{wat}} = (K_c)_a \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}}$$

TCPE

$$\begin{aligned} D_{\text{wat}} &= \beta_{\text{wat}} (K_c)_{\text{wat}} \\ &= \beta_{\text{wat}} A_c X \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}} \end{aligned}$$

$$D_{\text{wat}} = 0.876 \beta_{\text{wat}} A_c X \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}}$$

For x-ray beams higher than ^{60}Co : The C_λ concept

In phantom dosimetry for higher energies has been done on the basis of the C_λ concept.

C_λ is a conversion factor (rad/R) to derive the dose in rads at a point of reference in the water phantom from the reading of an ion chamber irradiated by the high energy x-ray beam

$$[D_{\text{wat}}]_\lambda = C_\lambda N_X A_{\text{ion}} MP_{\text{ion}}$$

Suppose an ion chamber which is a BG cavity with **water-equivalent** walls inside a water phantom. We ask that the same flux of secondary electrons cross the cavity as if the wall (and the buildup cap) were made of water.

The wall material does not have to be identical to water, provided that errors in collision stopping power and mass-energy absorption coefficients cancel each other.

Air and water equivalent are not very different (Fig. 2.2a). Plastics are too low in atomic number to imitate either water or air at low energies where the photoelectric effect is dominant, requiring the addition of some higher Z-element. The use of an aluminum rod on the central collecting electrode is a familiar method to adjust the low-energy air equivalence of an ion chamber.

As data showing discrepancies in the C_λ method using different ion chambers started to be published, there was a push to review the calibration protocols which culminated with the TG21 in US and others elsewhere.

Recently, calibration of absorbed dose in water instead of exposure has been proposed to make the calibration protocols even simpler.

Derivation of C_λ

- Two irradiations at the same point P in a water phantom, one with ^{60}Co and a second with a higher energy λ . The two irradiations are adjusted to give the same D_{gas}
- Applying BG relation

$$[D_{\text{wat}}]_{\text{Co}} = D_{\text{gas}} \left[\left(\frac{dT}{\rho dx} \right)_{e, \text{Co}} \right]_a^{\text{wat}}$$

$$[D_{\text{wat}}]_{\lambda} = D_{\text{gas}} \left[\left(\frac{dT}{\rho dx} \right)_{e, \lambda} \right]_a^{\text{wat}}$$

$$[D_{\text{wat}}]_{\lambda} = [D_{\text{wat}}]_{\text{Co}} \frac{[(dT/\rho dx)_{c,\lambda}]_a^{\text{wat}}}{[(dT/\rho dx)_{c,\text{Co}}]_a^{\text{wat}}}$$

$$D_{\text{wat}} = 0.876 \beta_{\text{wat}} A_c X \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}}$$

$$X = N_X A_{\text{ion}} MP_{\text{ion}}$$

$$[D_{\text{wat}}]_{\lambda} = \left[0.876 \beta_{\text{wat}} A_c \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}} \right]_{\text{Co}} \frac{\left[\left(\frac{dT}{\rho dx} \right)_{c,\lambda} \right]_a^{\text{wat}}}{\left[\left(\frac{dT}{\rho dx} \right)_{c,\text{Co}} \right]_a^{\text{wat}}} N_X A_{\text{ion}} MP_{\text{ion}}$$

$$C_{\lambda} = \left[0.876 \beta_{\text{wat}} A_c \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^{\text{wat}} \right]_{\text{Co}} \frac{\left[\left(\frac{dT}{\rho dx} \right)_{c,\lambda} \right]_a^{\text{wat}}}{\left[\left(\frac{dT}{\rho dx} \right)_{c,\text{Co}} \right]_a^{\text{wat}}} \quad (\text{rad/R})$$

Substitution of plastics to water in photon beam phantoms

TG21 specifically allowed calibrations in other materials than water to be done. This can be done provided the rules below are followed:

1. The center of the ion chamber should be positioned at the same distance from the source as if a water phantom is used. Also, the same beam collimator setting should be used.
2. The ion chamber walls (and ^{60}Co buildup cap) should preferably be made of the same plastic as the phantom.

3. The depth d_p of the chamber center from the front of the plastic phantom should be adjusted to give the same photon attenuation as would occur with the chamber at depth d_w in a water phantom

$$d_p = \frac{\rho_{\text{wat}}}{\rho_p} \cdot \frac{(\overline{Z/A})_{\text{wat}}}{(\overline{Z/A})_p} d_{\text{wat}}$$

$$= \left[\frac{0.5538}{\rho_p(\overline{Z/A})_p} \right] d_{\text{wat}}$$

TABLE 13.5. Ratios d_w/d_p for Polystyrene of Density 1.04 g/cm³ and Acrylic of Density 1.17 g/cm³ ^a

Radiation	d_w/d_p	
	Polystyrene	Acrylic
γ -Rays: ⁶⁰ Co	0.99	0.88
X-Rays (MV): 2-8	0.99	0.88
10-35	1.00	0.88
40-50	1.01	0.89

^aAAPM (1983). Reproduced with permission from R. J. Schulz and The American Institute of Physics.

4. The absorbed dose in plastic for a photon of beam quality λ is given by

$$(D_p)_\lambda = (C_\lambda)_p N_X A_{\text{ion}} M P_{\text{ion}} \quad (\text{rad})$$

$$(C_\lambda)_p = \left[0.876 \beta_p A_c \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^p \right]_{\text{Co}} \frac{\left[\left(\frac{dT}{\rho dx} \right)_{c, \lambda} \right]_a^p}{\left[\left(\frac{dT}{\rho dx} \right)_{c, \text{Co}} \right]_a^p}$$

5. Once the dose in plastic is known, one can derive the absorbed dose in water

$$(D_{\text{wat}})_\lambda = \beta_{\text{wat}}(K_c)_{\text{wat}} = \beta_{\text{wat}} \Psi \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_{\text{wat}}$$

$$(D_p)_\lambda = \beta_p(K_c)_p = \beta_p \Psi \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_p$$

$$(D_{\text{wat}})_\lambda = (D_p)_\lambda \left(\frac{\overline{\mu_{\text{en}}}}{\rho} \right)_p^{\text{wat}} \cdot \text{ESC}$$

TABLE 13.7. Excess-Scatter Correction (ESC) Factors for Measurements in Acrylic Phantoms^a

Photon	Depth in Phantom (cm)	ESC			
		Size ^b = 5 × 5	10 × 10	20 × 20	30 × 30
γ-Ray: ⁶⁰ Co	0.5	.997	.996	.995	.996
	5.0	.986	.987	.989	.991
x-Ray (MV): 2	0.4	.998	.994	.997	—
	5.0	.984	.982	.989	—
4	1.0	.998	.997	.998	—
	5.0	.994	.993	.993	—
6	1.5	.999	.998	.998	—
	5.0	.994	.994	.996	—

^aReproduced with permission from R. J. Schulz and The American Institute of Physics.

^bField size at depth (cm²).

Calibration of photon beams in phantoms by the N_{gas} method

A. Chamber wall material the same as phantom

Previously, we described the calibration of an ion chamber in terms of N_{gas} in a ^{60}Co gamma-ray beam. Now, we use the calibrated ion chamber to calibrate a photon beam.

$$(D_{\text{gas}})_{\lambda} = M_{\lambda} P_{\text{ion}} N_{\text{gas}}$$

The value of D_{gas} is typically larger than it would have been for a very small cavity located at P, due to lack of photon beam attenuation in the actual gas filled cavity. This is compensated by a replacement factor, which is a function of the gradient vs depth and the diameter of the cavity

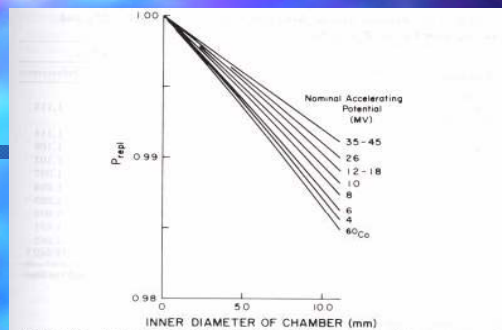


FIGURE 13.6. Replacement correction P_{repl} in water for ^{60}Co γ -rays and for x-rays generated at various energies (AAPM, 1983). Reproduced with permission from R. J. Schultz and The American Institute of Physics.

The absorbed dose $(D_{\text{wat}})_{\lambda}$ in the water at the point P in the absence of the chamber can be gotten by the application of the cavity theory

$$\begin{aligned} (D_{\text{wat}})_{\lambda} &= (D_{\text{gas}})_{\lambda} P_{\text{repl}} \left[\left(\frac{\bar{L}}{\rho} \right)_{\text{gas}}^{\text{wat}} \right]_{\lambda} \\ &= N_{\text{gas}} M_{\lambda} P_{\text{ion}} P_{\text{repl}} \left[\left(\frac{\bar{L}}{\rho} \right)_{\text{gas}}^{\text{wat}} \right]_{\lambda} \end{aligned}$$

B. Chamber wall different from phantom

$$(D_p)_\lambda = N_{\text{gas}} M_\lambda P_{\text{ion}} P_{\text{repl}} \times \left[\alpha \left(\frac{\bar{L}}{\rho} \right)_{\text{gas}}^{\text{wall}} \left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{wall}}^p + (1 - \alpha) \left(\frac{\bar{L}}{\rho} \right)_{\text{gas}}^p \right]_\lambda$$

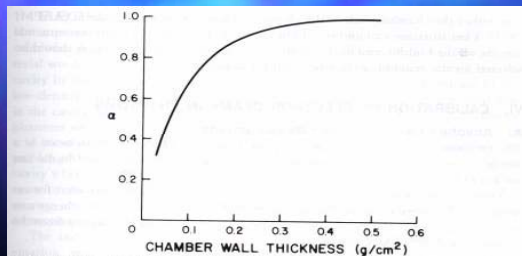


FIGURE 13.7a. Fraction α of ionization due to electrons arising in the chamber wall, as a function of mass wall thickness, for ^{60}Co γ -rays [Lempert et al. (1983), as adapted by AAPM (1983)]. Reproduced with permission from R. J. Schulz and The American Institute of Physics.

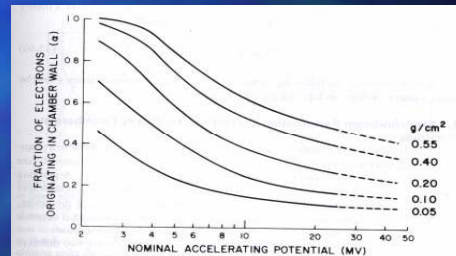


FIGURE 13.7b. Fraction α of ionization due to electrons from the chamber wall irradiated by x-rays with nominal acceleration potentials of 2 to 50 MV. The dashed portions of the curves are extrapolations of the experimental data. [Lempert et al. (1983), as adapted by AAPM (1983)]. Reproduced with permission from R. J. Schulz and The American Institute of Physics.

Calibration of electron beams in phantoms

- Absolute cavity-chamber measurements

$$D_p = D_{\text{gas}} \left[\left(\frac{dT}{\rho dx} \right)_c \right]_{\text{gas}}^p P_{\text{fl}}$$

$$D_p = D_{\text{gas}} \left[\left(\frac{\bar{L}}{\rho} \right)_\Delta \right]_{\text{gas}}^p P_{\text{fl}}$$

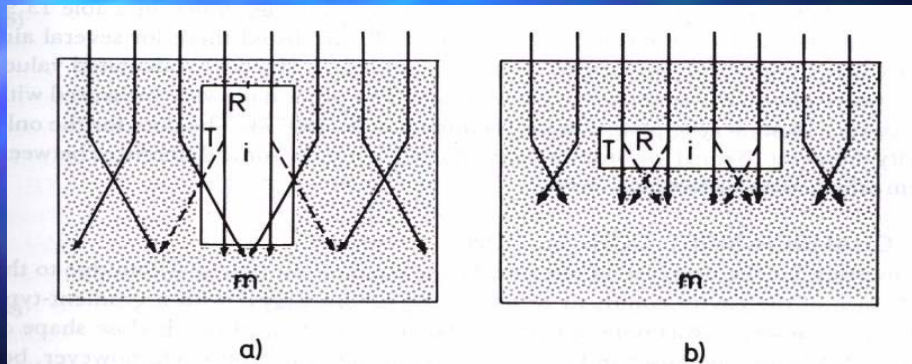
$$D_{\text{gas}} = (M_E P_{\text{ion}}/m) (\bar{W}/e)_{\text{gas}}$$

Electron-beam perturbations corrections for cavity chambers in phantoms

- A_c – displacement correction, is the fraction by which the exposure is decreased by broad beam photon attenuation in the water occupying the former void.
- $Prepl$ – is the fraction by which the D_{gas} should be decreased to compensate for the lack of photon-beam attenuation in the actual gas filled cavity.

- For electron beams the case is more complicated requiring two corrections
1. An electron-fluence scattering correction.
 2. Positioning of the chamber with its geometric center deeper in the phantom than the point P at which the dose is being determined.

Electron-fluence scattering correction



The in-scattering effect

The obliquity of pathlength effect

TABLE 13.9. Electron Fluence Correction Factor P_{fi} for Cylindrical Ion Chambers^a

\bar{T}^b (MeV)	P_{fi}					
	I.D. ^c = 3 mm	5 mm	6 mm	7 mm	10 mm	16 mm
1	—	— (.947)	—	—	—	—
2	.977	.962 (.970)	.956	.949	(.958)	—
3	.978	.966 (.978)	.959	.952	(.970)	(.962)
4	—	— (.984)	—	—	(.977)	(.972)
5	.982	.971 (.986)	.965	.960	(.981)	(.977)
7	.986	.977 —	.972	.967	—	—
10	.990	.985 (.992)	.981	.978	(.989)	(.987)
15	.995	.992 —	.991	.990	—	—
20	.997	.996 (.997)	.995	.995	(.995)	(.993)

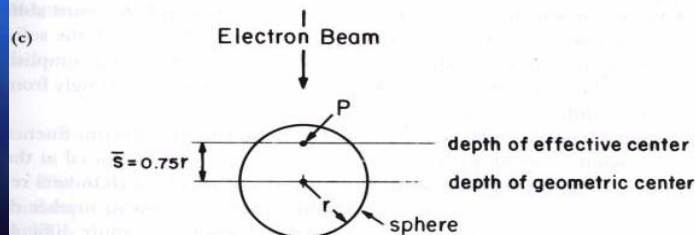
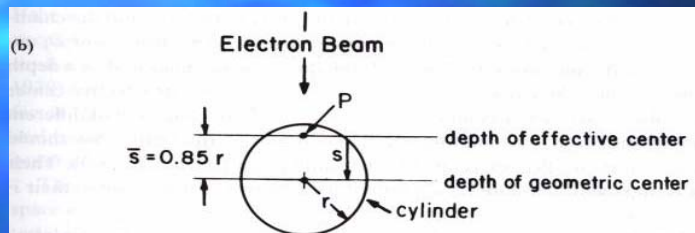
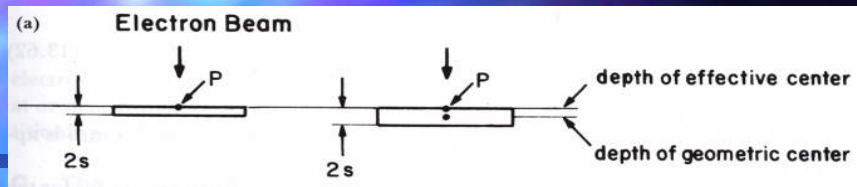
^aData in parentheses are for an air cavity in a water phantom, due to Harder (1968) as given in ICRU (1972). Other data are from acrylic-phantom measurements of Johansson et al. (1977), as given in AAPM (1983).

^bThe mean electron energy \bar{T} can be estimated for this purpose at the depth d of the effective chamber center by the equation $\bar{T} \cong T_0 [1 - d/(\text{CSDA range})]$, where T_0 is the incident energy of the electron beam, and the CSDA range of electrons of that energy is listed in Appendix E, column 5.

^cInner diameter.

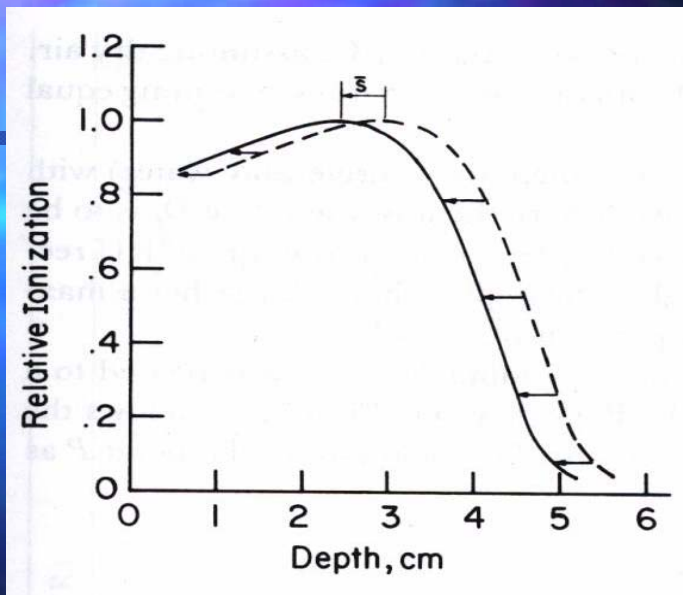
Chamber-shift correction

- A gradient type correction used in photon beams could be applied also for electron beams. The rapid change in dose as a function of depth discourages this approach.
- Alternative was proposed by Dutreix and Dutreix (1966) with a "displacement correction", where the geometric center of the chamber is displaced from the effective center of the chamber. Attix called it chamber-shift correction to distinguish it from the displacement correction for photons.



$$\bar{s} = \frac{\int_0^r (r^2 - x^2) dx}{\int_0^r (r^2 - x^2)^{1/2} dx} = \frac{8r}{3\pi} \cong 0.85r$$

$$\bar{s} = \frac{\int_0^r x(r^2 - x^2) dx}{\int_0^r x(r^2 - x^2)^{1/2} dx} = \frac{3r}{4} = 0.75r$$



The C_E method

- This is similar to the C_λ method.
- The value of CE is obtained through a ^{60}Co gamma-ray calibration in which the exposure is X (C/kg). The ion chamber wall and buildup cap are made of material w , and the cavity contains air. The dose in the cavity air is

$$D_a = X \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^w A_w \beta_w \left(\frac{\overline{L}}{\rho} \right)_w^a$$

$$= MP_{\text{ion}} N_X A_{\text{ion}} \left(\frac{\overline{W}}{e} \right)_a \left(\frac{\mu_{\text{en}}}{\rho} \right)_a^w A_w \beta_w \left(\frac{\overline{L}}{\rho} \right)_w^a$$

- The ICRU (1972) made the implicit assumption that the chamber wall and buildup cap were exactly air-equivalent for ^{60}Co γ -rays, and $\beta_w = 1.000$ and $P_{\text{ion}} A_{\text{ion}} = 1.000$

$$D_a = MN_X \left(\frac{\overline{W}}{e} \right)_a A_w$$

- The ion chamber is then placed in a phantom of medium p with the effective center of the ion chamber at the point where the absorbed dose D_p is to be determined

$$D_p = (D_a)_E \left[\left(\frac{dT}{\rho dx} \right)_{c,a} \right]^p P_{\text{fl}}$$

$$= M_E P_{\text{ion}} N_X A_{\text{ion}} \left(\frac{\overline{W}}{e} \right)_a A_w \left[\left(\frac{dT}{\rho dx} \right)_{c,a} \right]^p P_{\text{fl}}$$

- If N_x is given instead in R/C and D_p is in rad

$$D_p = 0.876 M_E P_{\text{ion}} N_X A_{\text{ion}} A_w \left[\overline{\left(\frac{dT}{\rho dx} \right)}_c \right]^p P_{\text{fl}}$$

$$= M_E P_{\text{ion}} N_X A_{\text{ion}} C_E$$

$$C_E = 0.876 A_w \left[\overline{\left(\frac{dT}{\rho dx} \right)}_c \right]^p P_{\text{fl}} \text{ rad/R}$$

The N_{gas} method

An ion chamber calibrated in terms of N_{gas} can be used for electron beams. The chamber wall need not exactly match the phantom medium, p , so long as the wall is fairly thin (e.g. 0.1 g/cm²) and of low atomic number plastic. A matching buildup cap, increasing the wall thickness has to be added during the ⁶⁰Co γ -rays calibration.

$$D_p = N_{\text{gas}} M_E P_{\text{ion}} P_{\text{fl}} \left[(L/\rho)_{\text{gas}}^p \right] \bar{T}$$

TG 51 Protocol

Obtain an absorbed dose to water calibration factor for the user ion chamber from NIST or an ADCL.
This factor is good for T=22 and P=760 mmHg and relative humidity between 20 to 80%, respectively.

$$D_w^Q = MN_{D,w}^Q \quad (\text{Gy}),$$

$$N_{D,w}^{60\text{Co}} = \frac{D_w^{60\text{Co}}}{M} \quad (\text{Gy/C or Gy/rdg}),$$

$$N_{D,w}^Q = k_Q N_{D,w}^{60\text{Co}} \quad (\text{Gy/C or Gy/rdg}),$$

← Quality conversion factor

For photons

- k_Q is tabulated for different commercial ion chambers

TABLE I. Values of k_Q for accelerator photon beams as a function of $\%dd(10)_x$ for cylindrical ion chambers commonly used for clinical reference dosimetry. Values calculated as described in Refs. 45 and 51. The tabulated values can be interpolated linearly in $\%dd(10)_x$. The ion chamber specifications used in these calculations are found in Table III. Figure 4 presents the same data within 0.1%. For ^{60}Co beams, $k_Q = 1.000$ by definition.

Ion chamber	k_Q					
	58.0	63.0	66.0	71.0	81.0	93.0
Capintec PR-05/PR-05P	0.999	0.997	0.995	0.990	0.972	0.948
Capintec PR-06C/G 0.6cc Farmer	1.000	0.998	0.994	0.987	0.968	0.944
Exradin A1 Shonka ^a	0.999	0.998	0.996	0.990	0.972	0.948
Exradin A12 Farmer	1.000	0.999	0.996	0.990	0.972	0.948
NE2505/3,3A 0.6cc Farmer	1.000	0.998	0.995	0.988	0.972	0.951
NE2561 0.3cc NPL Sec. Std ^b	1.000	0.998	0.995	0.989	0.974	0.953
NE2571 0.6cc Farmer	1.000	0.998	0.995	0.988	0.972	0.951
NE2577 0.2cc	1.000	0.998	0.995	0.988	0.972	0.951
NE2581 0.6cc robust Farmer	1.000	0.994	0.988	0.979	0.960	0.937
PTW N30001 0.6cc Farmer ^c	1.000	0.996	0.992	0.984	0.967	0.945
PTW N30002 0.6cc all Graphite	1.000	0.997	0.994	0.987	0.970	0.948
PTW N30004 0.6cc Graphite	1.000	0.998	0.995	0.988	0.973	0.952
PTW 31003 0.3cc waterproof ^d	1.000	0.996	0.992	0.984	0.967	0.946
Wellhofer IC-10/IC-5	1.000	0.999	0.996	0.989	0.971	0.946

^aThe cavity radius of the A1 here is 2 mm although in the past Exradin has designated chambers with another radius as A1.

^bThe NE2611 has replaced the equivalent NE2561.

^cPTW N30001 is equivalent to the PTW N23333 it replaced.

^dPTW N31003 is equivalent to the PTW N233641 it replaced.

For electrons

$$k_Q = P_{\text{gr}}^Q k_{R_{50}},$$

Gradient correction

$$k_{R_{50}} = k'_{R_{50}} k_{\text{ecal}}.$$

Photon electron conversion

k_{ecal} converts the ^{60}Co calibration factor to the clinical electron beam calibration factor

$k'_{R_{50}}$ converts the clinical electron beam calibration factor to the calibrated electron beam calibration factor