<u>Calibration of Ion Chambers and Photon Beams – 'TG-21':</u>

(electron beams briefly near the end)

- Since other classes and training in the future will dwell on the newer clinical protocol, 'TG-51,' we will only discuss this in a comparative way after first exploring this older and outdated protocol: 'TG-21.' The reasons for this are both that it is still used (unfortunately), and more importantly, the physics is more transparent. By learning this first, it will be easy to understand TG-51 later. *The analogy is that it is easy to learn to drive with an automatic transmission after one learns to drive with a manual transmission first. <u>TG-21 is analogous to the manual transmission car.</u>*

- The basic issue is that each clinical linac beam is different in 'quality.' In other words, it will have some uniqueness to its energy spectrum. One 'dials-in' a 'monitor unit.' The monitor unit, MU, is calibrated to give 1cGy at reference conditions. It would be deceptive to have "cGy" on the linac dial since it would give the false impression that it was always calibrated !

- Involved in this 'reference condition' is an ion chamber. That ion chamber and its electrometer too need to be calibrated. The only way to do this, considering that each linac has a unique energy spectrum, and each chamber has a unique charge collection volume at a microscopic level, is to send the chamber and electrometer to a place with a Co-60 source that is itself well calibrated.

- In the United States, the various Accredited Dosimetry Calibration Laboratories (ADCL) do this very task. They work in concert with the National Institute of Standards and Technology (NIST) to maintain the source: Co-60 always has the same beam quality! It only gets less radioactive in time. Note that in our Medical Physics Department, we have an ADCL !!!

- These calibration laboratories can provide the 'exposure' from the Co-60 source in a volume of air. They can characterize your ion chamber's response to their source. They provide that 'response' to you in the form of a factor called N_x, and you then use all the physics we have just learned, wrapped in factors that we will now learn about, to be able to determine what the dose in the reference condition is for your linac. Then, you will be able to adjust the linac, if needed, to provide for 1 MU = 1 cGy at the reference conditions, and the patients will get their planned dose to well within 1% from physics considerations alone (neglecting all biology!).

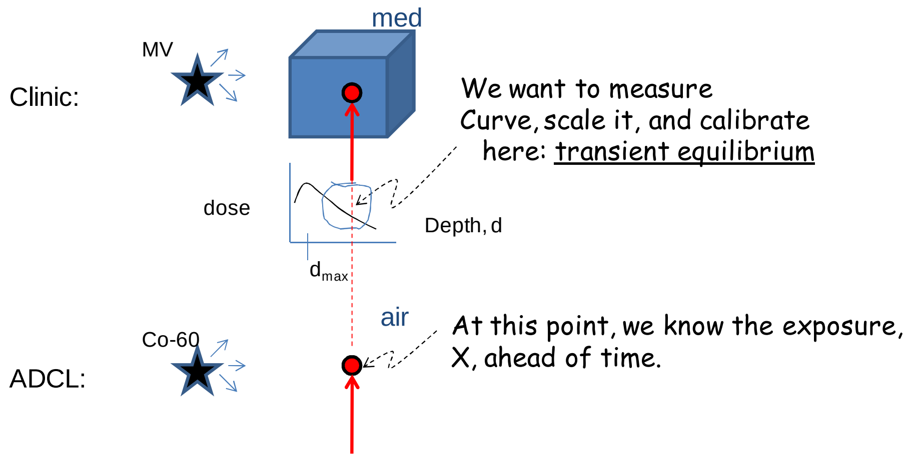
- The TG-21 protocol is the result of a Task Group from the American Association of Physicists in Medicine (AAPM). It is published in the Medical Physics journal: Med. Phys. Vol. 10, issue 6, 1983, pp. 741-771:

A protocol for the determination of absorbed dose from high-energy photon and electron beams•

Task Group 21, Radiation Therapy Committee, American Association of Physicists in Medicine•

- NOTE: Some notations will change: for example, 'M' will be the charge now.

- **Understanding TG-21 at the NIST Cal. Lab or ADCL:**



- In the chamber is a 'gas.' It is almost always air, but in the protocol they write "gas" for the air inside the chamber! The word "air" will refer to the air in the ADCL room. So, at the NIST lab (or ADCL), they put the chamber and electrometer in their Co-60 beam and get the relation between the exposure and the dose to the chamber gas.

- The NIST lab knows X, the exposure. A clinician's chamber is placed where they know X, and a reading, M, is obtained (units of charge, C). That reading is corrected to 22°C and 1atm. The value of N_x is obtained:

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

-- if less than 300keV, it can be directly measured with a free-air ionization chamber! Otherwise, it can be carefully calculated as described below.

- We also know that the dose to the chamber gas is found by:

$$D_{gas} = J_{gas}\left(\frac{\overline{W}}{e}\right)_{gas}$$

-- Where we define J_{gas} as the <u>charge per unit mass of the cavity gas</u> (usually, almost always, anytime I can think of, 'air'). The energy deposited for an ion pair for room air (not dry air) in our energy range is provided to be 33.7 J/C. The J_{gas} is assumed to be corrected for recombination here, so if not, write $D_{gas} = (J_{gas}A_{ion})\left(\frac{\overline{W}}{e}\right)_{gas}$.

- Before we go further … How **did the NIST lab get X** ?

- They know and calculated X from a variety of measurements, see **Eq. 1 of TG-21** and preceding text.

$$X = k^{-1}J_{gas}\left(\frac{\overline{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{wall}^{air}\beta_{wall}^{-1}\left(\prod_i K_i\right)$$

Where,

1. **We assume a Spencer-Attix cavity theory** for the chamber, $\therefore \left(\frac{\overline{L}}{\rho}\right)_{gas}^{wall}$

2. We assume the photon energy fluence through the room air is unperturbed by the chamber wall, $\therefore \left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{wall}^{air}$ at zero thickness: <u>further corrected below</u> with A_{wall}.

3. k =2.58x10^{-4} C/kg/R

4. β_{wall} = the ratio of dose to collision Kerma in the chamber wall = 1.005 (i.e., the ADCL must use a carbon wall to get 'X').

5. These 'K' factors represent water vapor content of the room air, ionization recombination losses, scatter from stem of chamber, correction to zero wall

thickness, and some other factors: $\prod_i K_i \cong \frac{1}{A_{ion}A_{wall}}$,

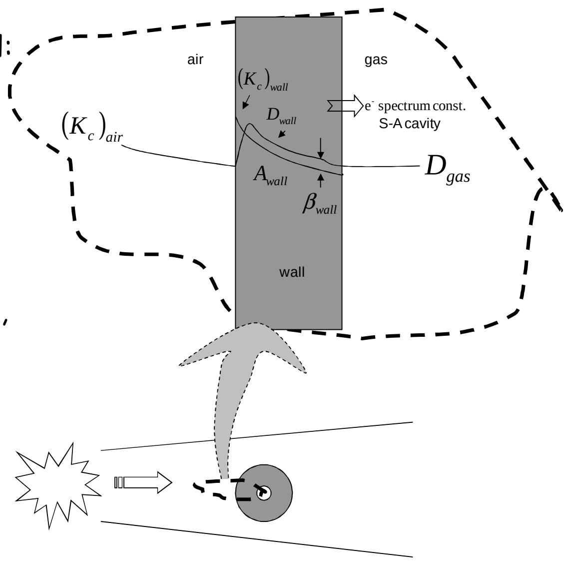
Where,

-- **A_{ion} accounts for ion recombination losses** for the Co-60 beam: it is Q'/Q in our previous notation: the ratio of charge collected to charge produced in the cavity gas: the charge collection efficiency, f.

-- **A_{wall} accounts for the wall thickness effects** different from zero on the collision Kerma.

- Let's build up this equation from basic principles TG – 21; We will use A_{ion} and N_x to calculate N_{gas} which is a property of the chamber and build-up cap, but not the phantom in the clinic !

-- Relating dose in chamber gas to dose in wall:



0: $D_{gas} = \left(\frac{D_{gas}}{D_{wall}}\right)[D_{wall}]$

-- Wall dose in TCPE, a build-up (β_{wall}) from its collision Kerma (graphite walls w/ Co-60, see text near Eq. 1 in TG-21):

1: $D_{gas} = \left(\frac{D_{gas}}{D_{wall}}\right)[\beta_{wall}(K_c)_{wall}]$

{Note: wall includes cap (α=1),

i.e., same z_{eff} for now. Also, β_{wall} is a correction for

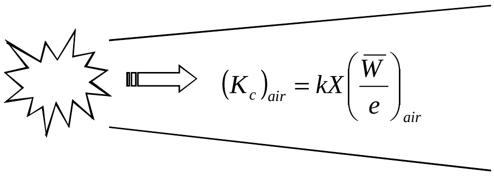
charged particle fluence changes actually}

-- relate to Kerma in the room air (at the ADCL):

2: $D_{gas} = \left(\frac{D_{gas}}{D_{wall}}\right)\left[\beta_{wall}\left\{\frac{(K_c)_{wall}}{(K_c)_{air}}\right\}(K_c)_{air}\right]$

-- The room air Kerma – the ADCL room air !! :

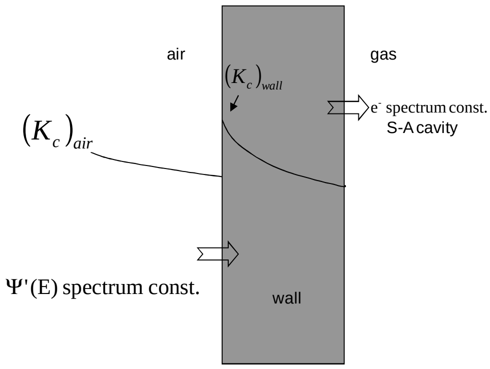
$$3:\ D_{gas} = \left(\frac{D_{gas}}{D_{wall}}\right)\left[\beta_{wall}\left\{\frac{(K_c)_{wall}}{(K_c)_{air}}\right\}kX\left(\overline{W}/e\right)_{air}\right]$$



{Note that $\left(\overline{W}/e\right)_{air}$ is <u>not</u> a function of beam energy!}

-- Assume photon energy spectrum unperturbed until corrected for attenuation in the wall (A_{wall})*:

$$4:\ D_{gas} = \left(\frac{D_{gas}}{D_{wall}}\right)\left[A_{wall}\beta_{wall}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{air}^{wall} kX\left(\overline{W}/e\right)_{air}\right]$$



{Note: wall includes cap (α=1),

i.e., same z_{eff} for now}

-- Spencer-Attix cavity theory applies#:

$$5:\ D_{gas} = \left(\frac{\overline{L}}{\rho}\right)_{wall}^{gas}\left[A_{wall}\beta_{wall}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{air}^{wall} kX\left(\overline{W}/e\right)_{air}\right]$$

* Note the photon fluence correction: $A_{wall} = e^{-\mu' t} \cong 1-(\mu'/\rho)\rho t$. Note that the photon fluence correction is decoupled from the charged particle fluence correction: β_{wall} for Co-60 beam at ADCL.

#Note: Bragg-Gray would have been OK, errors of only a few tenths of a percent if the wall is almost water equivalent. The $\Delta = 10keV$ and the R_{CSDA} in air is 0.25cm. The following table shows the error if one were to use Bragg-Gray:

TABLE 13.2. Comparison of $[(\overline{L}/\rho)^g_w]_{\Delta=10\ keV}$ and $[(dT/\rho dx)_c]^g_w$ for g = Air and w = Several Typical Cavity-Chamber Wall Materials and Water[a]

Wall	$[(\overline{L}/\rho)^g_w]_{\Delta=10\ keV}$	$[(dt/\rho dx)_c]^g_w$
Polystyrene	0.899[b]	0.905[c]
Lucite	0.907	0.910
Graphite	0.990	0.991
C552 air-equiv. plastic	1.000	1.000
Water	0.883	0.886

[a]For ^{60}Co γ-rays.
[b]Data in this column are from AAPM (1983).
[c]Data in this column are from Johns & Cunningham (1983).

- <u>BUT, let's go further for a bit ...</u>

-- Relate X to ***charges collected***: M

{ Note that: $N_x = X / M$ }

6: $D_{gas} = \left(\frac{\overline{L}}{\rho}\right)^{gas}_{wall} \left[A_{wall} \beta_{wall} \left\{\frac{\mu_{en}}{\rho}\right\}^{wall}_{air} MkN_X \left(\overline{W}/e\right)_{air} \right]$

-- rearrange to get: and

{**relate now to *charges liberated***: M / A_{ion} :

Note that: recombination losses = A_{ion}}

7: $D_{gas} = M \left[A_{wall} \beta_{wall} \left(\frac{\overline{L}}{\rho}\right)^{gas}_{wall} \left\{\frac{\mu_{en}}{\rho}\right\}^{wall}_{air} N_X k \left(\overline{W}/e\right)_{air} \right]$

-- Note that:

$D_{gas} = J_{gas}\left(\overline{W} / e\right)$, and this is Eq. 3 of TG-21 (J_{gas} is said to include A_{ion}).

$D_{gas} = N_{gas}\left(M / A_{ion}\right)$, and this is Eq. 4 of TG-21.

- Define now:

$$N_{gas} \equiv A_{wall}\beta_{wall}\left(\frac{\overline{L}}{\rho}\right)_{wall}^{gas}\left\{\frac{\mu_{en}}{\rho}\right\}_{air}^{wall} A_{ion} N_X k \left(\overline{W}/e\right)_{air}$$

or re-arranging:

- We have now derived Eq. 5 in TG-21:

$$N_{gas} = N_X \frac{A_{wall}\beta_{wall}A_{ion}k\left(\overline{W}/e\right)_{air}}{\left(\frac{\overline{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{wall}^{air}}$$

-- An advantage of N_{gas} is that it is a property only of the chamber!

-- Note that all of these are for Co-60 beam quality – it is a correction that takes this out so that another beam quality can be used for this chamber.

- Now, if we get N_x from the NIST lab, we can use this to calculate N_{gas} such that N_{gas} has the meaning: $D_{gas} = M \cdot N_{gas}$. 'M' is corrected for recombination.

- BE CAREFUL: TG-21 gets confusing with where A_{ion} gets included or not ! Also, M here must be corrected for temperature and pressure.

- **The NIST lab gives us N_x and A_{ion}.** What happens next? At the clinic, we need to calculate N_{gas} ourselves ! Then, we will have our own correction factors:

- **P-factors for the clinic VERSUS A-factors for the NIST lab !**

- **Understanding TG-21 at the Clinic:**

- In the clinic, we will have a medium, a phantom, even if it is just a build-up cap. The beam energy is also different, and it is pulsed.

- TG-21 says all we need is TCPE in the phantom (medium), and suggests the following depths: {Aside … rule of thumb: $d_{\max}(cm) \sim E(MV)/4$}

Beam Nominal Energy (MV)	Depth (cm)
Co-60 - 15	5
16 - 25	7
26 - 50	10

- Use the same field size as was done at calibration: 10 cm x 10 cm typically.

- More general than just TG-21: Take a reading, M, but again, it must be corrected for temperature and pressure and some other things at this stage. Later, other factors are explicitly corrected for outside of 'M'. For now, we correct M as follows:

$$M = M_{raw} \cdot P_{t,p} \cdot P_h \cdot P_{pol}$$

-- Note that the temperature and pressure correction is as you would expect:

$$P_{t,p} = \frac{273.15K + T(^oC)}{295.15K} \cdot \frac{760torr}{p(torr)}$$

-- The humidity correction, for a wide range of average humidity, is just unity.

-- The polarity correction is more explicit in TG-51, but here, one should do the following with $M^{+/-}$ is the raw reading at a + or - polarity:

$$P_{pol} = \frac{(M^+ - M^-)}{[2(M^+ or M^-)]}$$

-- Polarization effects are caused by

1. Compton current: electrons liberated from other stuff like electrodes and guard.
2. Extracameral current: cable irradiation or charges collected outside of gas sensitive volume.

- Then we calculate N_{gas} and calculate the dose to the gas in the cavity.

-- The dose to the cavity gas is:

$$D_{gas} = (M \cdot P_{ion}) N_{gas}$$

-- Note, we also needed to use **a different factor for the ion recombination losses:** $\mathbf{P_{ion}}$, but strangely enough, it is the inverse (Q/Q') of A_{ion}. Most common ion chambers have $\mathbf{P_{ion} = 1/A_{ion}}$ ~ 1 anyway … $(M \cdot P_{ion})$ is charged liberated, and M is charges collected! Expect very small or very large chambers to have complicated recombination dynamics.

The **older** approach to recombination is as follows: $P_s = a_0 + a_1\left(\frac{R_1}{R_2}\right) + a_2\left(\frac{R_1}{R_2}\right)^2$

Where: R_1 is read at -300v, and R_2 is read at -100v for example.

- The dose to the medium is built up the same way as before …

8: $D_{med} = \left(\frac{D_{med}}{D_{gas}}\right) D_{gas}$

-- Let's assume Spencer-Attix also applies here. $\therefore \left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}$ can be substituted for $\left(\frac{D_{med}}{D_{gas}}\right)$ provided we use factors described next because we skipped the wall in this ratio. If it is very different from the phantom, it can be accounted for:

-- **P_{repl} allows us to use Spencer-Attix** by correcting for the photon fluence perturbations caused by the whole chamber's displacement of the medium. It does not include electron fluence corrections if the chamber is placed at TCPE ($d>d_{max}$).

Attix figure 13.6

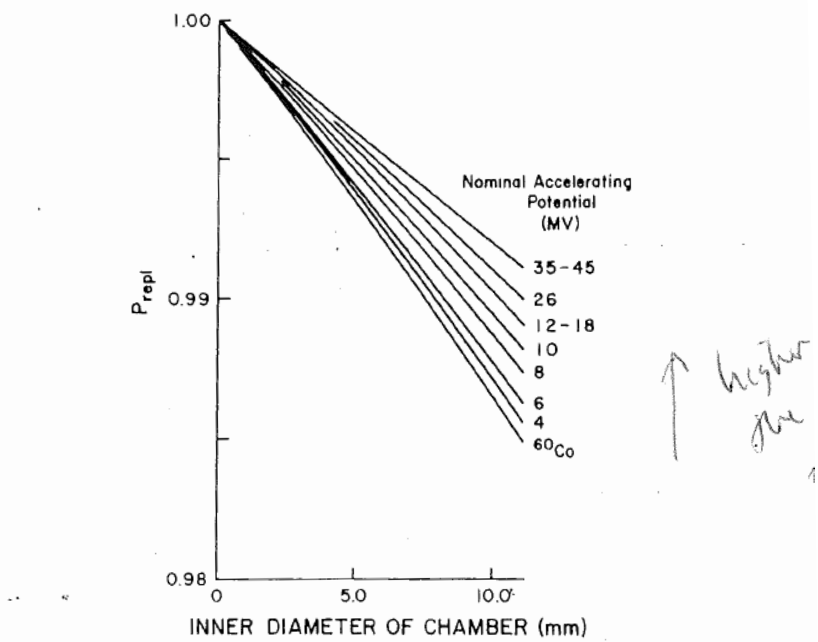


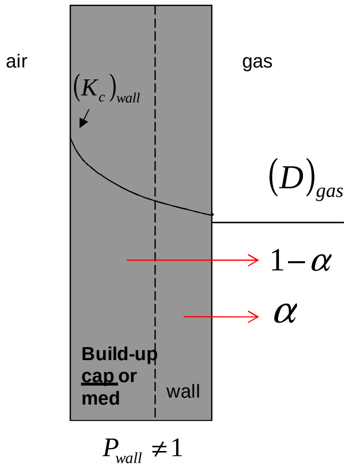
FIGURE 13.6. Replacement correction P_{repl} in water for ^{60}Co γ-rays and for x-rays generated at various energies (AAPM, 1983). Reproduced with permission from R. J. Schulz and The American Institute of Physics.

-- Also, **a factor for the medium different from the wall** (P_{wall}). What if the medium and the wall material both provide electrons to the cavity gas ? If different materials and both provide charges to the gas in the cavity, then $P_{wall} \neq 1$.

-- **IMPORTANT NOTE**: There are scatter corrections that we are leaving out of the dose calculation. In Medical Physics 566, this is calculated and is more related to the linac and set-up conditions, and it is decided that this is beyond the scope of this class.

- Our original picture is used to show the effect: *sort of* like Burlin theory in reverse! Except there is no very large cavity here …

-- **Use α, the fraction of ionizations in the cavity gas by electrons from the wall, proper. Therefore, 1-α is that fraction from the medium or the phantom instead.** Now, use these fractions in N_{gas} Eq. 6 TG-21:



$$N_{gas} = N_X \frac{A_{wall}\beta_{wall}A_{ion}k\left(\overline{W}/e\right)_{air}}{\alpha\left(\frac{\overline{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{wall}^{air} + (1-\alpha)\left(\frac{\overline{L}}{\rho}\right)_{gas}^{med}\left\{\frac{\overline{\mu}_{en}}{\rho}\right\}_{med}^{air}}$$

-- all of these are for Co-60. Find α in Fig. 1 for Co-60 (Fig. 7 is for another quality).

- **Let's dig into this a bit further …**

-- at the ADCL: $A_{wall} = \frac{\psi_{wall}}{\psi_{air}} \Rightarrow \frac{\psi_{wall}}{\psi_{med}}$, air is the 'medium'!

-- at the clinic: $\frac{D_{med}}{D_{gas}} = \overbrace{\frac{D_{med}}{D_{wall}}}^{P_{repl}\text{ covers it}} \cdot \frac{D_{wall}}{D_{gas}} \Rightarrow P_{repl}\underbrace{(P_{wall}=1)}_{same\_material}\left(\frac{\overline{L}}{\rho}\right)_{gas}^{med}$

- So, with the same material of wall and medium, then P_{wall}=1 by definition! (and for electron beams)

- Otherwise use:

$$P_{wall} = \frac{\alpha\left(\frac{\bar{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{wall}^{med} + (1-\alpha)\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}}{\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}}$$

- Therefore, from Fig. 7, for beam quality, Q:

$$\boxed{D_{med} = M \cdot N_{gas}\left(P_{ion} \cdot P_{wall} \cdot P_{repl}\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}\right)}$$

This is Eq. 9 in TG-21

- Here is how these complimentary terms are handled in the protocol:

-- at the ADCL, replace: "in-air" at ADCL: all for Co-60, use Fig. 1 for α.

$$\left(\frac{\bar{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{wall}^{air} \Rightarrow \alpha\left(\frac{\bar{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{wall}^{air} + (1-\alpha)\left(\frac{\bar{L}}{\rho}\right)_{gas}^{cap}\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{cap}^{air}$$

-- $P_{wall} \neq 1$ at the clinic, replace: {relate to Eq. 10 in TG-21} "in-phantom" at clinic, use Fig. 7 for α.

$$\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med} P_{wall} \Rightarrow \alpha\left(\frac{\bar{L}}{\rho}\right)_{gas}^{wall}\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{wall}^{med} + (1-\alpha)\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}\underbrace{\left\{\frac{\bar{\mu}_{en}}{\rho}\right\}_{med}^{med}}_{=1!}$$

- Note: A_{wall} is unaffected by α, and A_{wall} corrects only for photons.

- **Note that 'gas' and 'air' must be distinguished to derive all this; the worksheet at the end of TG-21 does not distinguish !!!! (bug in TG-21 I think).**

-- More on α: from Attix, but is the same as Fig. 1 in TG-21 (for Co-60):

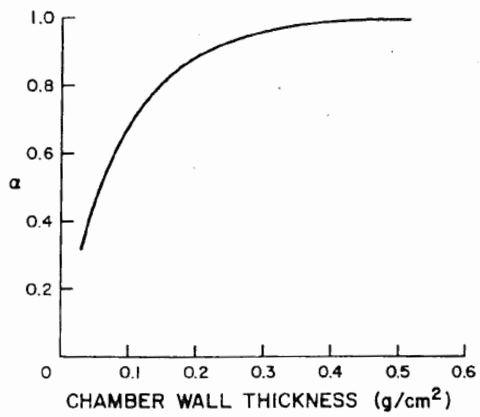


FIGURE 13.7a. Fraction α of ionization due to electrons arising in the chamber wall, as a function of mass wall thickness, for ^{60}Co γ-rays [Lempert et al. (1983), as adapted by AAPM (1983)]. Reproduced with permission from R. J. Schulz and The American Institute of Physics.

-- if not Co-60, use Fig. 7:

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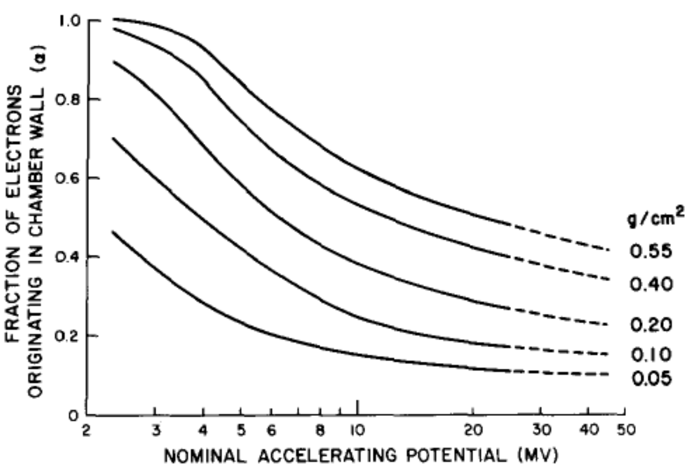


FIG. 7. Fraction of ionization (α) due to electrons from the chamber wall irradiated by x rays with nominal accelerating potentials of 2–50 MV. The dashed portions of the curves are extrapolations of experimental data (Ref. 20).

-- Also note that Table II gives wall + cap thickness.

- With the above factors, from step 8 above: (α=1)

9: $$D_{med} = \left(P_{ion} P_{wall} P_{repl} \left(\frac{\bar{L}}{\rho} \right)_{gas}^{med} \right)_Q D_{gas}$$

-- substitute now with step 7 above to *finally* get: (α=1)

10: $$D_{med} = M \left(P_{ion} P_{wall} P_{repl} \left(\frac{\bar{L}}{\rho} \right)_{gas}^{med} \right)_Q \left[A_{wall} \beta_{wall} \left(\frac{\bar{L}}{\rho} \right)_{wall}^{gas} \left\{ \frac{\bar{\mu}_{en}}{\rho} \right\}_{air}^{wall} A_{ion} N_X k \left(\overline{W} / e \right)_{air} \right]_{Co-60}$$

-- rearrange to see more clearly: (α=1)

$$D_{med} = \underbrace{\left(M P_{ion} A_{ion} \right)}_{1} \cdot \overbrace{\left(P_{wall} P_{repl} A_{wall} \beta_{wall} \right)}^{2} \cdot \underbrace{\left[N_X k \left(\overline{W} / e \right)_{air} \right]}_{3} \cdot \overbrace{\left[\left\{ \frac{\bar{\mu}_{en}}{\rho} \right\}_{\substack{air \\ Co-60}}^{\substack{wall \\ Co-60}} \left(\frac{\bar{L}}{\rho} \right)_{\substack{wall \\ Co-60}}^{\substack{gas \\ Co-60}} \left(\frac{\bar{L}}{\rho} \right)_{\substack{gas \\ Q}}^{\substack{med \\ Q}} \right]}^{4}$$

Discussion of each part's corrections:

1. **Recombination**: Chamber/electrometer reading M, corrected for recombination difference between continuous Co-60 (A_{ion}) and the pulsed linac (P_{ion}).
2. **Fluence**: For ADCL, Co-60, β_{wall} corrects for Φ (charges), and ψ (photons) are corrected for by A_{wall}. Then, for the clinic linac, both are corrected for by the product: $P_{wall} P_{repl}$. The higher energy linac has a coupled correction! Again, $P_{wall} = 1$ if $\alpha = 1$
3. **Energy corresponding to a charge pair** in the ADCL, so that we can use $\mathbf{N_x}$.
4. **Attenuation and Stopping Power** corrections.

This is what we do at the clinic for photon beams!

-- substitute the N_{gas} definition in '10' above to get Eq. 9 of TG-21.

11: $$D_{med} = M \underbrace{\left(P_{ion} P_{wall} P_{repl} \left(\frac{\overline{L}}{\rho} \right)_{gas}^{med} \right)}_{\substack{all\_for\_clinic\_specific \\ beam\_Q\_and\_phantom \\ corrected\_into\_it}} \underbrace{\left[N_{gas} \right]}_{\substack{property\_of\_chamber \\ Co-60\_corrected\_out}}$$

- <u>**Calibration of Electron Beams (briefly, since this is outdated):**</u>

- The situation is that we have N_{gas}, and let us suppose that we have a thin wall or one that matches the phantom (medium or cap) material.

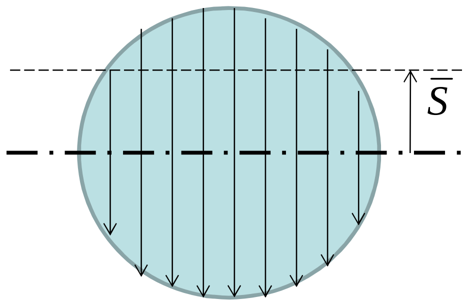
- <u>The dose in the phantom from an electron beam</u> with mean energy, $\overline{T}$, crossing the cavity is the following:

$$\left(D_{med} \right)_{\overline{T}} = M_E \left(P_{ion} P_{fl} \left(\frac{\overline{L}}{\rho} \right)_{gas}^{med} \right)_{\overline{T}} \left[N_{gas} \right]$$

- $\left(D_{med} \right)_{\overline{T}}$ is the dose at the average point at which electrons enter the cavity which is displaced a distance *upstream* of the geometric center of the cavity:

Cavity type	Dimension	$\overline{S}$
Parallel	d = thickness	d/2
Cylindrical	r = radius	0.85r
Spherical	r = radius	0.75r

Depth of the effective center of the ion chamber:

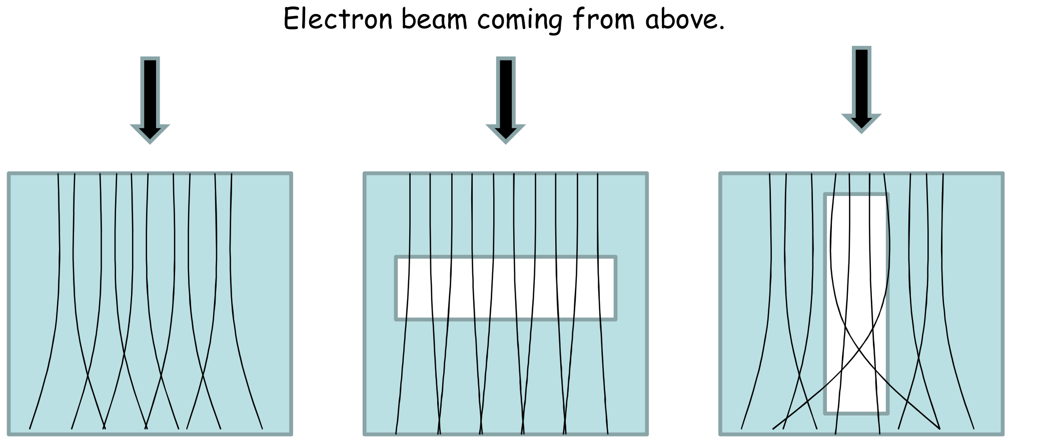


- M_E is the pressure and temperature corrected electrometer reading in the electron beam.

- P_{fl} is the electron fluence correction. Only very small cavities will not perturb an electron beam. This perturbation is mainly due to a spatial variation of scatter. Thin parallel plate chambers have $P_{fl} \approx 1$, and extrapolation chambers can extrapolate to $P_{fl} = 1$.

- See Attix table 13.9 for P_{fl} for cylindrical chambers. It is < 1, and gets smaller for lower electron energies in cylindrical chambers.

- The following figures show the effects of differently shaped cavities on the electron scattering – the effects can be complex:



Homogeneous phantom

Phantom with cavity: Wide: less scattering and decreased dose in the cavity.

Phantom with cavity: Long: more in-scattering and increased dose in the cavity.

- $\left(\left(\frac{\bar{L}}{\rho}\right)_{gas}^{med}\right)_{\bar{T}}$ is the ratio of restricted stopping powers evaluated at the average energy $\bar{T}$. The TG-21 protocol recommends $\Delta = 10 keV$.

  -- Recall that the average electron energy decreases linearly with depth, R_p is the practical range, d is the depth beneath the surface, and T_0 is the energy of the beam at the surface:

$$\bar{T} \cong T_0(1 - d / R_p)$$

  {Attix uses the CSDA range …, but TG-21 uses the practical range …}

- The table on the next page, from Attix, has the ratio of restricted stopping powers for water polystyrene and lucite. Notice that it increases with decreasing energy for water or plastic phantoms.

- Attix table 13.11 (also can see table 13.13):

TABLE 13.11. $[(L/\rho)^{p}_{air}]_{\overline{T}}$ **for Use in Eq. (13.69); Phantom Medium = Water**[a]

Depth	$[(L/\rho)^{p}_{air}]_{\overline{T}}$, Δ = 10 keV															
(g/cm²)	T_o[b] = 60.0	50.0	40.0	30.0	25.0	20.0	18.0	16.0	14.0	12.0	10.0	9.0	8.0	7.0	6.0	5.0
0.0	0.902	0.904	0.912	0.928	0.940	0.955	0.961	0.969	0.977	0.986	0.997	1.003	1.011	1.019	1.029	1.040
0.1	0.902	0.905	0.913	0.929	0.941	0.955	0.962	0.969	0.978	0.987	0.998	1.005	1.012	1.020	1.030	1.042
0.2	0.903	0.906	0.914	0.930	0.942	0.956	0.963	0.970	0.978	0.988	0.999	1.006	1.013	1.022	1.032	1.044
0.3	0.904	0.907	0.915	0.931	0.943	0.957	0.964	0.971	0.979	0.989	1.000	1.007	1.015	1.024	1.034	1.046
0.4	0.904	0.908	0.916	0.932	0.944	0.958	0.965	0.972	0.980	0.990	1.002	1.009	1.017	1.026	1.036	1.050
0.5	0.905	0.909	0.917	0.933	0.945	0.959	0.966	0.973	0.982	0.991	1.003	1.010	1.019	1.028	1.039	1.054
0.6	0.906	0.909	0.918	0.934	0.946	0.960	0.967	0.974	0.983	0.993	1.005	1.012	1.021	1.031	1.043	1.058
0.8	0.907	0.911	0.920	0.936	0.948	0.962	0.969	0.976	0.985	0.996	1.009	1.016	1.026	1.037	1.050	1.067
1.0	0.908	0.913	0.922	0.938	0.950	0.964	0.971	0.979	0.988	0.999	1.013	1.021	1.031	1.043	1.058	1.076
1.2	0.909	0.914	0.924	0.940	0.952	0.966	0.973	0.981	0.991	1.002	1.017	1.026	1.037	1.050	1.066	1.085
1.4	0.910	0.916	0.925	0.942	0.954	0.968	0.976	0.984	0.994	1.006	1.022	1.032	1.044	1.058	1.075	1.095
1.6	0.912	0.917	0.927	0.944	0.956	0.971	0.978	0.987	0.997	1.010	1.027	1.038	1.050	1.066	1.084	1.104
1.8	0.913	0.918	0.929	0.945	0.957	0.973	0.981	0.990	1.001	1.014	1.032	1.044	1.057	1.074	1.093	1.112
2.0	0.914	0.920	0.930	0.947	0.959	0.975	0.983	0.993	1.004	1.018	1.038	1.050	1.065	1.082	1.101	1.120
2.5	0.917	0.923	0.934	0.952	0.964	0.981	0.990	1.000	1.013	1.030	1.053	1.067	1.083	1.102	1.120	1.131
3.0	0.919	0.926	0.938	0.956	0.969	0.987	0.997	1.008	1.023	1.042	1.069	1.084	1.102	1.119	1.129	
3.5	0.922	0.929	0.941	0.960	0.971	0.994	1.004	1.017	1.034	1.056	1.085	1.102	1.118	1.128		
4.0	0.924	0.932	0.944	0.964	0.979	1.001	1.012	1.027	1.046	1.071	1.101	1.116	1.126			
4.5	0.927	0.935	0.948	0.969	0.985	1.008	1.021	1.037	1.059	1.086	1.115	1.125	1.127			
5.0	0.929	0.938	0.951	0.973	0.990	1.016	1.030	1.049	1.072	1.101	1.123	1.126				
5.5	0.931	0.940	0.954	0.978	0.996	1.024	1.040	1.061	1.086	1.113	1.125					
6.0	0.934	0.943	0.958	0.983	1.002	1.033	1.051	1.074	1.100	1.121						
7.0	0.938	0.948	0.965	0.993	1.017	1.054	1.075	1.099	1.118	1.122						
8.0	0.943	0.954	0.972	1.005	1.032	1.076	1.098	1.116	1.120							
9.0	0.947	0.960	0.981	1.018	1.049	1.098	1.114	1.118								
10.0	0.952	0.966	0.990	1.032	1.068	1.112	1.116									
12.0	0.962	0.980	1.009	1.062	1.103											
14.0	0.973	0.996	1.031	1.095	1.107											
16.0	0.986	1.013	1.056	1.103												
18.0	1.000	1.031	1.080													
20.0	1.016	1.051	1.094													
22.0	1.032	1.070														
24.0	1.048	1.082														
26.0	1.062	1.085														
28.0	1.071															
30.0	1.075															

[a] AAPM (1983). Reproduced with permission from R. J. Schulz and The American Institute of Physics.
[b] Electron-beam energies T_o (MeV) are those at phantom entry.

- There is more to discuss here, but with too much detail on electrons, it moves us too far from the course's focus. For example, calibration is at dmax, and it will <u>not</u> include a gradient correction, P_{repl}. It does include an electron fluence correction. Note also that P_{wall} = 1 for parallel plate electron chambers, or is the walls are < 0.5 mm thick.

- Next lecture: a bit about TG-51 and why it's better.