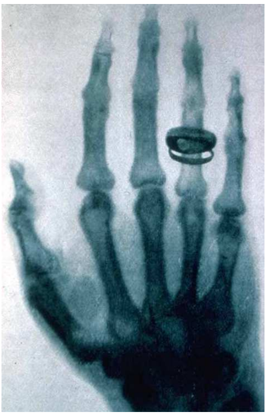
Ionization Chambers

Measurement of Exposure

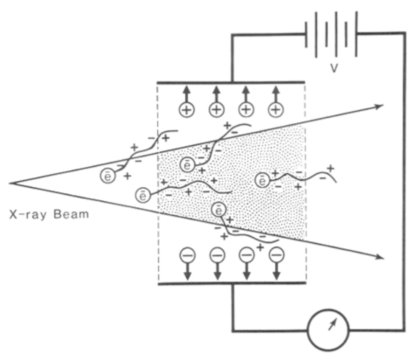


$$X = \frac{dQ}{dm}$$

The Roentgen

- The Roentgen is a unit of exposure, which is a measure of ionization produced ***in air*** by photons
- The ICRU defines exposure (*X*) as the quotient of *dQ* by *dm*, where *dQ* is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated in air of a mass *dm* are completely stopped in air
- The SI unit fir exposure is coulomb per kilogram (*C/Kg*)
- The special unit is the Roentgen
- 1R = 2.58 x 10^{-4} C/kg air

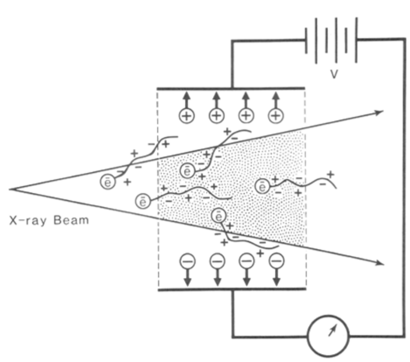
Measurement of Exposure



The Roentgen

- An x-ray beam in air sets in motion electrons by the photoelectric effect, Compton scattering, and and/or pair production
- These high-speed electrons produce ionization along their tracts
- If a voltage is applied between two plates, the positive electrons will move toward the negative plate, and the negative charges move toward the positive plate
- The collected charge of either sign can be measured with an electrometer

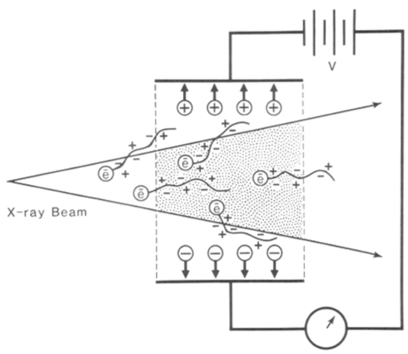
Measurement of Exposure



The Roentgen

- According to the definition of a roentgen, the electrons produced by photons in a specific volume must spend all their energies by ionization in air enclosed by the plates
- Some electrons produced in the specific volume deposit their energy outside the region of ion collection (*and are not measured*)
- Other electrons produced outside the region of ion collection may enter this region and produce ionizations

Measurement of Exposure



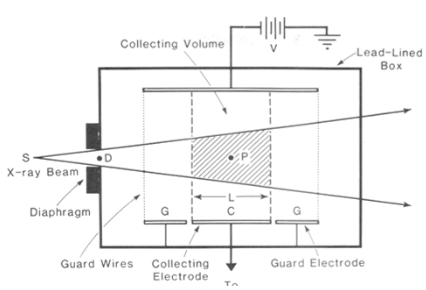
The Roentgen

- A condition of electronic equilibrium exists when the ionization loss equals the ionization gain
- Only under this condition is the definition of the roentgen satisfied

Free-Air Ionization Chamber

- The free-air (*or standard*) ion chamber is an instrument used to measure the exposure (*i.e. the number of Roentgens*)
- Generally, free-air ionization chambers are used are used to calibrate secondary instruments

Measurement of Exposure

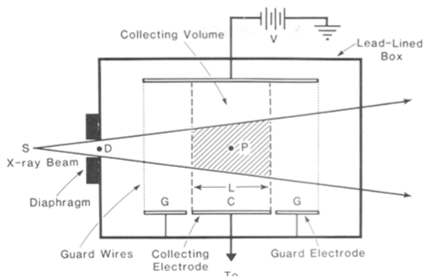


$$X = \frac{\Delta Q}{\rho A L} \frac{1}{2.58 \times 10^{-4}}$$

Free-Air Ionization Chamber

- An x-ray beam originating from focal spot *S*, is defined by the diaphragm *D*, and passes centrally between a pair of parallel plates
- A high-voltage field (*100 V/cm*) is applied between the plates to collect ions produced in the air between the plates
- The ionization is measured for a length *L* defined by the limiting lines of force to the edges of the collection plate *C.*
- The lines of force ore made straight and perpendicular to the collecting volume by a guard ring *G*

Measurement of Exposure

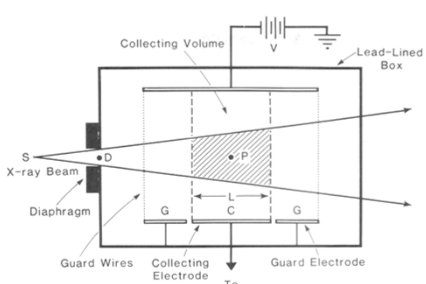


$$X = \frac{\Delta Q}{\rho A L} \; \frac{1}{2.58 \times 10^{-4}}$$

Free-Air Ionization Chamber

- The electrons produced by the photon beam in the specified volume must spend all their energy by ionization of air between the plates
- Such a condition can only exist if the range of the electrons liberated by the incident photons is less than the distance between each plate and the specified volume
- In addition, for electronic equilibrium to exist, the beam intensity must remain constant across the length of the specific volume

Measurement of Exposure



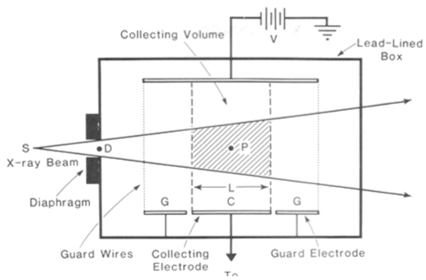
$$X = \frac{\Delta Q}{\rho A L} \; \frac{1}{2.58 \times 10^{-4}}$$

Free-Air Ionization Chamber

- Accurate measurements require considerable care
- Several corrections are made:
  - Air attenuation
  - Recombination of ions
  - Temperature
  - Pressure
  - Humidity
  - Ionization for scattered photons

Measurement of Exposure

Free-Air Ionization Chamber

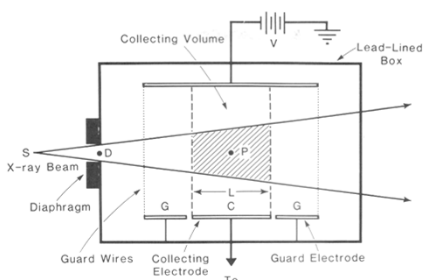


$$X = \frac{\Delta Q}{\rho A L} \; \frac{1}{2.58 \times 10^{-4}}$$

- There are several limitations on the design of a free-air chamber for the measurement of Roentgens for high-energy x-ray beams
- As the photon energy increases, the range of electrons liberated in air increases rapidly
- This necessitates an increase in the separation of the plates to maintain electronic equilibrium
- Too large a separation creates a problem with non-uniform electric fields and ion recombination

Measurement of Exposure

Free-Air Ionization Chamber



$$X = \frac{\Delta Q}{\rho A L} \; \frac{1}{2.58 \times 10^{-4}}$$

- The plate separation could be reduced by using air at high pressure
- However, the problems of air attenuation, photon scatter, and reduction in ion collect efficiency still remain
- Because of these limitations, 3 MeV is the upper limit on photon energy above which the roentgen cannot be currently defined
- These ion chambers are generally too delicate and bulky for routine use

Measurement of Dose

Radiation Absorbed Dose

- The exposure (*roentgen*) is only defined in air for <3 MeV photons
- Absorbed dose was developed to describe the quantity of radiation for all types of ionizing radiation in all materials and all energies
- The current definition of the absorbed dose is the energy departed to material of a given mass
- The old unit of dose was the rad, which represents 10^{-2} J/kg
- The SI unit for absorbed dose is the gray (*Gy*), which equals 1 J/kg

$1 \text{ rad} = 10^{-2} \text{ J/kg}$

$1 \text{ Gy} = 1 \text{ J/kg}$

$1 \text{ Gy} = 100 \text{ rad}$

$1 \text{ rad} = 1 \text{ cGy}$

Measurement of Dose

Absorbed Dose to Air

- Exposure (*X*) can be converted to absorbed dose (*D*) under conditions of electronic equilibrium
- However, this conversion is limited to photon energies < 3 MeV
- The mean energy required to produce an ion pair ($\overline{W}$) in dry air is almost constant for all electron energies
- If *e* is the electric charge, then $\overline{W}$ / e is the average energy required per unit charge of ionization

$$\frac{\overline{W}}{e} = 33.97 \text{ J/C}$$

$$D_{air} = X \frac{\overline{W}}{e}$$

$$D_{air} = X \cdot [2.58 \times 10^{-4} \text{ (C/kg)}] \cdot [33.97 \text{ (J/C)}]$$

$$= 0.876 \times 10^{-2} \text{ (Gy/R)} \cdot X(R)$$

$$= 0.876 \text{ (cGy/R)} \cdot X(R)$$

Measurement of Dose

$$\frac{D_{med}}{D_{air}} = \frac{(\mu/\rho)_{med}}{(\mu/\rho)_{air}} \frac{(\Psi)_{med}}{(\Psi)_{air}}$$

$$D_{med} = X \frac{\overline{W}}{e} \frac{(\mu/\rho)_{med}}{(\mu/\rho)_{air}} \frac{(\Psi)_{med}}{(\Psi)_{air}}$$

$$= 0.876\, X \frac{(\mu/\rho)_{med}}{(\mu/\rho)_{air}} \frac{(\Psi)_{med}}{(\Psi)_{air}}$$

$$= f_{med}\, X\, A$$

Absorbed Dose to Medium

- In the presence of electronic equilibrium, the absorbed dose (D) to a medium can be calculated from the energy fluence (Ψ) and the weighted mean mass energy absorption coefficient
- Suppose that Ψ_{air} is the energy fluence at a point in air, and Ψ_{med} is the energy fluence at a point in medium
- Under electronic equilibrium conditions, the doses are related
- The quantity f_{med} is the f factor

Measurement of Dose

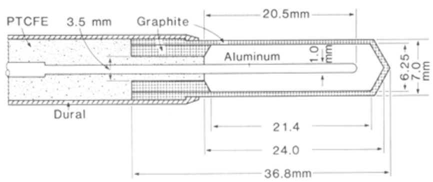
Photon Energy (keV)	f Factor					
	Water		Bone		Muscle	
	(Gy kg/C)	(rad/R)	(Gy kg/C)	(rad/R)	(Gy kg/C)	(rad/R)
10	35.3	0.911	134	3.46	35.7	0.921
15	34.9	0.900	149	3.85	35.7	0.921
20	34.6	0.892	158	4.07	35.6	0.919
30	34.3	0.884	164	4.24	35.6	0.918
40	34.4	0.887	156	4.03	35.7	0.922
50	34.9	0.900	136	3.52	36.0	0.929
60	35.5	0.916	112	2.90	36.3	0.937
80	36.5	0.942	75.1	1.94	36.8	0.949
100	37.1	0.956	56.2	1.45	37.1	0.956
150	37.5	0.967	41.2	1.06	37.2	0.960
200	37.6	0.969	37.9	0.978	37.2	0.961
300	37.6	0.970	36.5	0.941	37.3	0.962
400	37.6	0.971	36.2	0.933	37.3	0.962
600	37.6	0.971	36.0	0.928	37.3	0.962
1000	37.6	0.971	35.9	0.927	37.3	0.962
2000	37.6	0.971	35.9	0.927	37.3	0.962

Data from Wyckoff HO. (Communication.) Med Phys 1983;10:715. Calculations are based on energy absorption coefficient data from Hubbell JH. Photon mass attenuation and energy-absorption coefficients from 1 keV to 20 MeV. Int J Appl Radiat Isotop 1982;33:1269.

Absorbed Dose to Medium

- The *f* factors are often listed in tables for various energies
- For water and soft tissue, the ratio of the mean mass energy absorption coefficients vary slowly with energy (*~10% variation from 10 keV to 10 MeV)*
- Bone has a much larger *f* factor between 10 keV to 100 keV due to the photoelectric effect
- At the higher energies where Compton is the predominate interaction all *f* factors are similar

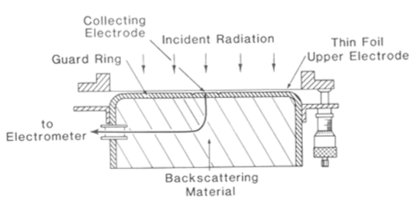
Ionization Chambers



Farmer Chamber

- In 1955, Farmer designed an ionization chamber that provided a stable and reliable secondary standard for x-rays at all energies in the therapeutic range
- This chamber was later modified by Farmer in 1972 to provide a flatter energy response and more consistency of design from one chamber to another
- The thimble wall is made of pure graphite, and the central electrode is pure aluminum
- The collecting volume of the chamber is typically 0.6 cm^3

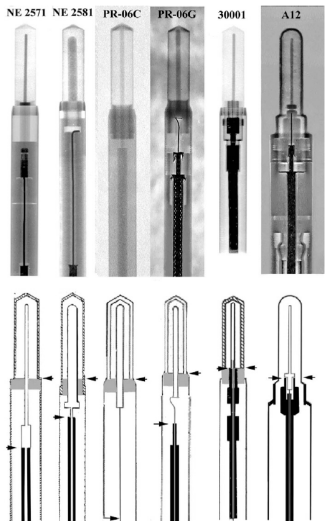
Ionization Chambers



Parallel Plate Chamber

- The beam enters through a thin foil that is typically 0.01- to 0.03-mm thick
- This plate is made of Mylar, polystyrene, or Mica, which allows measurements to be made at the surface of the chamber without significant wall attenuation
- The lower collecting electrode is coin shaped, and is surrounded by a guard ring
- The electrode spacing is ~ 2-mm, which minimizes cavity perturbations in the field

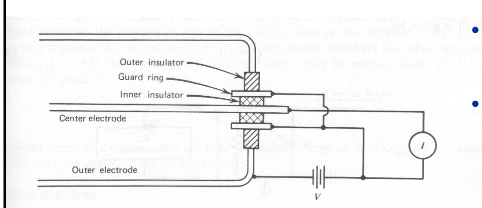
Ionization Chambers



Chamber Imaging

- Radiographs and drawings (below) of five Farmer-style ion chambers plus an Exradin A12
- In the drawings, the heavy black lines represent the extent of guarding, as also indicated by the arrows on the left.
- The grey blocks indicate the insulator in closest contact with the active air volume, indicated by the arrows on the right.
- The A12 has no insulator other than air in contact with the active air volume

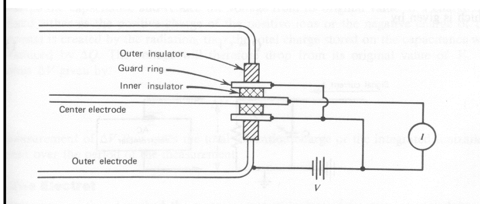
Ionization Chambers



Guard Ring

- A supporting insulator must be used between the two electrodes
- Because the ionization currents in most applications are extremely small (*10^{-12} Amps)*, the leakage current through the insulator must be very small
- Any leakage through the insulator will add to the measured ionization current, and cause an unwanted component to the signal
- In order to keep this component below 1%, would require the insulator to have a resistance of 10^{16} ohms

Ionization Chambers



Guard Ring

Although it may be possible to find such an insulator, it would be bulky and moisture would lower the resistance

A guard ring is typically used in ion chambers to reduce the effects of insulator leakage

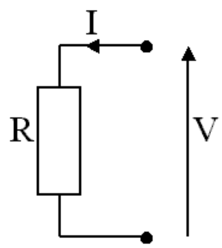
- The insulator is divided into two parts
  - *One part separates the conducting guard ring from the negative electrode*
  - *The second part separates the conducting guard ring from the positive electrode*

Ionization Chambers

Triaxial Cable

- Triaxial cable is used to connect the ionization chamber to the electrometer
- It is circular is cross-section, and consists of three parts that are each separated by an insulating material
  - *A center conductor made of a solid or braided wire*
  - *A concentric solid or braided conductor*
  - *Another concentric solid or braided conductor*

Electrometers



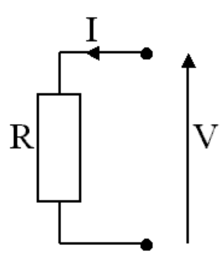
$$\frac{V}{I} = R \qquad V = I \cdot R$$

$$C = \frac{Q}{V} \qquad \mathrm{I} = \mathrm{Q/t}$$

Electrometers

- The SI unit for electric charge is the coulomb, which represents 6.24 x 10^{18} elementary charges (*the charge of a single electron or proton*)
- The coulomb (*Q*) is defined as the quantity of charge that has passed through the cross-section of a conductor carrying one ampere with one second
- The SI unit for electrical current (*I*) is the ampere
- One ampere of current (*I*) is equal to the flow of one coulomb of charge (*Q*) per second of time (*t*)

Electrometers



$$\frac{V}{I} = R \qquad V = I \cdot R$$

$$C = \frac{Q}{V} \qquad \mathrm{I} = \mathrm{Q/t}$$

Electrometers

- Ohm's law states that the potential difference (*or voltage drop*) between the ends of a conductor and the current (*I*) are proportional
- The capacitance is a measure of the amount of electric charge stored for a given electric potential
- The electrometer is an electrical instrument used for measuring charge (*Q*)
- The charge is measured using Ohm's Law and the capacitance relationship

Electrometers

Electrometers

- Voltage is measured by comparing the input voltage with a internal reference voltage using a circuit with a high impedance (*10^{14} ohms)*
- An amplifier magnifies small currents
- A current-to-voltage converter allows the measurement of tiny currents (*10^{-15} ohms)*
- The known capacitance can be used to calculate the electric charge to a fraction of a picocoulomb

Dose in Medium

$$D_{med} = J_g \frac{\overline{W}}{e} (S/\rho)_g^{med}$$

J_g = *Ionization Charge*

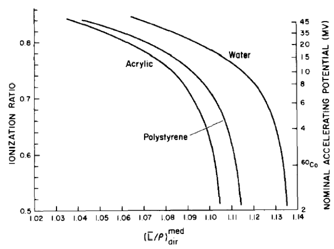
$(S/\rho)_g^{med}$ = *weighted mean ratio of the mess stopping power of the medium to that of the gas*

Bragg-Gray Cavity Theory

- The Bragg-Gray cavity theory is used to calculate dose directly from ion chamber measurements in a medium
- The ionization produced in a gas-filled cavity placed in medium is related to the energy absorbed in the surrounding medium
- When the cavity is sufficiently small so that its introduction into the medium dose not alter the number or distribution of the electrons that would exist in the medium without the cavity

Dose in Medium

$$\bar{L}/\rho = \frac{\int_{\Delta}^{E_0} \Phi(E)\cdot L/\rho(E)\,dE}{\int_{\Delta}^{E_0} \Phi(E)\,dE}$$

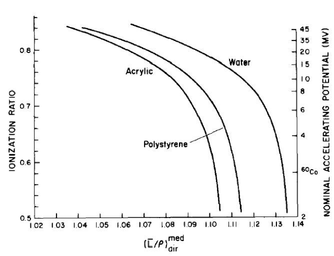


Spencer-Attix Formulation

- The term stopping power refers to the energy loss by electrons per unit path length of a material
- To use stopping power ratios in the Bragg-Gray formula, it is necessary to determine a weighted mean of the stopping power ratios for the electron spectrum set into motion by the photons (*which also have an energy spectrum*)
- The Spencer-Attix formulation is an approximation technique that has a cut-off energy for secondary electrons

Dose in Medium

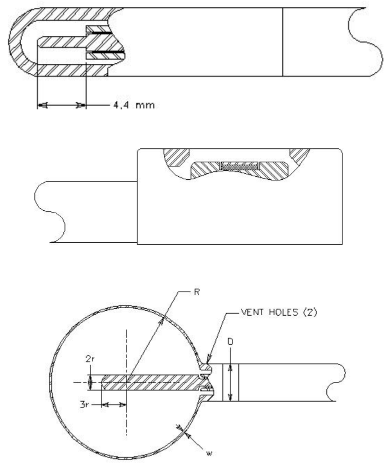
$$\bar{L}/\rho = \frac{\int_{\Delta}^{E_0} \Phi(E)\cdot L/\rho(E)\,dE}{\int_{\Delta}^{E_0} \Phi(E)\,dE}$$



Spencer-Attix Formulation

- The restricted mass collision stopping power is given by *L/ρ*
- The primary electrons give rise to secondary electrons
- In the Spencer-Attix formulation, secondary electrons below an arbitrary energy limit (*Δ*) are assumed to deposit their energy near the site of origin
- The value of *Δ* for most ionization chambers will lie between 10 and 20 keV

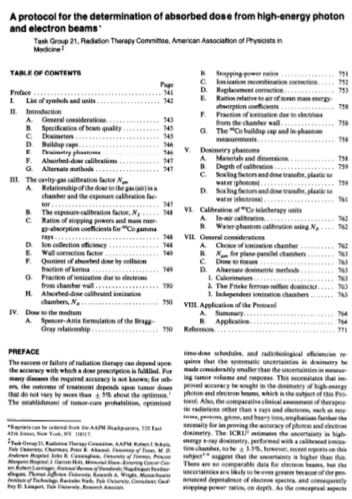
Dose in Medium



Chamber Volume

- The Ionization Charge (J_g) can be determined for a chamber of known volume, or for a known mass of air in the chamber
- However, the chamber volume is not known to an acceptable accuracy
- Most ion chambers used for therapy measurements are vented to the atmosphere
- The National Institu of Standard and Technology (*NIST*) specifies standard conditions as 22C and 760 mmHg

TG-21 Calibration

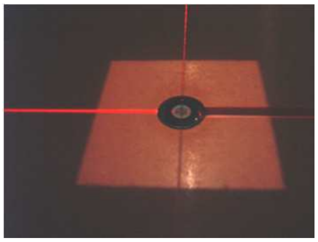

A protocol for the determination of absorbed dose from high-energy photon and electron beams*

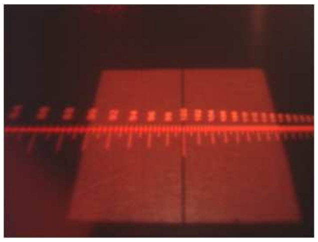
Task Group 21, Radiation Therapy Committee, American Association of Physicists in Medicine‡

Machine Calibration

- Absorbed dose calibration of a clinical radiation beam required that a nationally, or internationally approved protocol be followed
- The American Association of Physicists in Medicine (*AAPM*) published a calibration standard in 1986
- The Task Group (*TG*) 21 protocol is the old standard for photon and electron calibration
- The Task Group (*TG*) 51 protocol is the new standard for photon and electron calibration

TG-21 Calibration



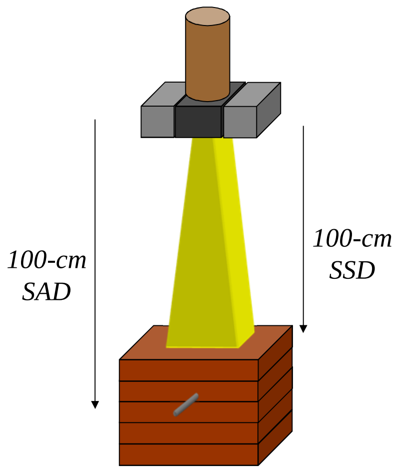


Geometry

- The calibration geometry for TG21 can vary from institution to institution
- However, it is typically:
  - *100-cm to the surface of the phantom (SSD calibration)*

    or
  - *100-cm to the center of the chamber (SAD calibration)*
  - *10 x 10 Field Size at Isocenter*
  - *10-cm Depth*

TG-21 Calibration

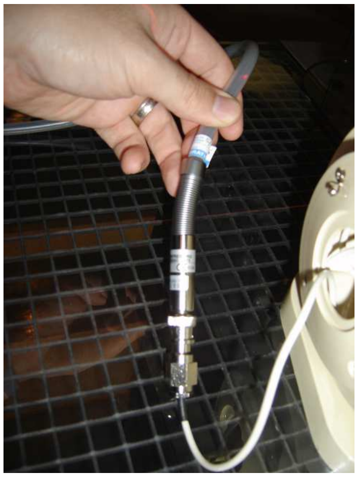


Geometry

- The calibration geometry for TG21 can vary from institution to institution
- However, it is typically:
  - *100-cm to the surface of the phantom (SSD calibration)*

    or
  - *100-cm to the center of the chamber (SAD calibration)*
  - *10 x 10 Field Size at Isocenter*
  - *10-cm Depth*

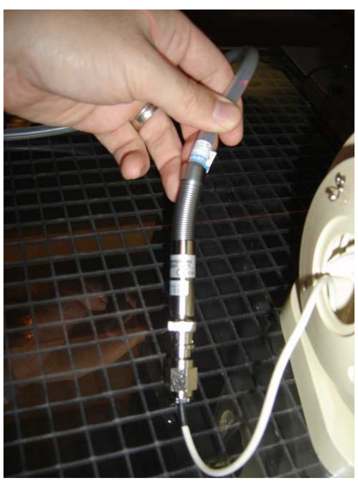
TG-21 Calibration



Chamber Calibration

- Each ionization chamber that is used for calibration must be calibrated every two years by the NIST or an Accredited Dosimetry Calibration Lab
- The Calibration Report provides the user with a factor that is dependant on the chambers characteristics (*volume, build-up cap, wall material, etc…*)
- This factor is determined by exposing your chamber to a Cobalt-60 beam with a known exposure rate
- NIST uses a special spherical, graphite ion chamber of known volume to measure the known exposure rate

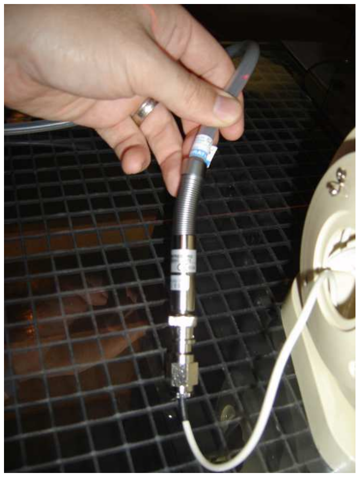
TG-21 Calibration



Chamber Calibration

- The chamber calibration factor (*Nx*) is provided (*for TG-21 calibrations*) in R/C and is normalized to 22C and 760mmHg
- The cavity-gas calibration factor (*Ngas*) must be calculated from Nx
- Ngas is defined as the dose to the gas in the chamber per unit charge (*or electrometer reading*)
- Since the volume of gas is not known accurately, it is determined indirectly from Nx

TG-21 Calibration



Chamber Calibration

- If Ngas is not given, then it must be calculated:

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

- Tables have been published with the ratio’s of Ngas to Nx
- These Ratios do not vary greatly between commonly used chambers

TG-21 Calibration

$$D_{med} = M\, N_{gas} (\bar{L}/\rho)^{med}_{gas} P_{ion}\, P_{repl}\, P_{wall}$$

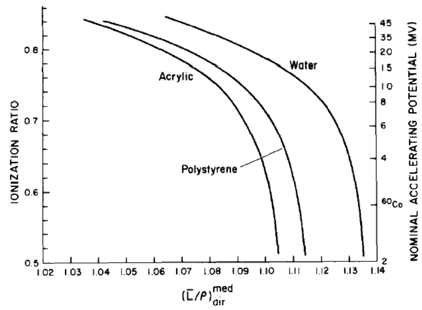
Electrometer Measurement

- The electrometer must be set to 300V (*positive or negative bias*)
- The Temperature and Pressure must be corrected to STP
- [P] = 760 mmHg
- [T] = 273 + T in °C

$$\boxed{M = M_{raw} ({}^{T}/_{295})\, ({}^{760}/_{P})}$$

TG-21 Calibration

$$D_{med} = M\, N_{gas} (\bar{L}/\rho)^{med}_{gas} P_{ion}\, P_{repl}\, P_{wall}$$



Nominal accelerating potential (MV)	$(\bar{L}/\rho)^{med}_{air}$ Water	Polystyrene	Acrylic	Graphite	A-150	C-552	Bakelite	Nylon
2	1.135	1.114	1.104	1.015	1.154	1.003	1.084	1.146
^{60}Co	1.134	1.113	1.103	1.012	1.151	1.000	1.081	1.142
4	1.131	1.108	1.099	1.007	1.146	0.996	1.075	1.136
6	1.127	1.103	1.093	1.002	1.141	0.992	1.070	1.129
8	1.121	1.097	1.088	0.995	1.135	0.987	1.063	1.120
10	1.117	1.094	1.085	0.992	1.130	0.983	1.060	1.114
15	1.106	1.083	1.074	0.982	1.119	0.972	1.051	1.097
20	1.096	1.074	1.065	0.977	1.109	0.963	1.042	1.087
25	1.093	1.071	1.062	0.968	1.106	0.960	1.038	1.084
35	1.084	1.062	1.053	0.958	1.098	0.952	1.027	1.074
45	1.071	1.048	1.041	0.939	1.087	0.942	1.006	1.061

Mass Stopping Power

- L/ρ is dependant on the incident photon energy
- During the TG21 calibration process, the energy is measured by taking measurements at two depths
- The ionization ration is the ratio of the reading at 20-cm depth to the reading a 10-cm depth
- The ionization radio will always be less than 1.00

TG-21 Calibration

$$D_{med} = M\, N_{gas} (\bar{L}/\rho)^{med}_{gas} P_{ion}\, P_{repl}\, P_{wall}$$

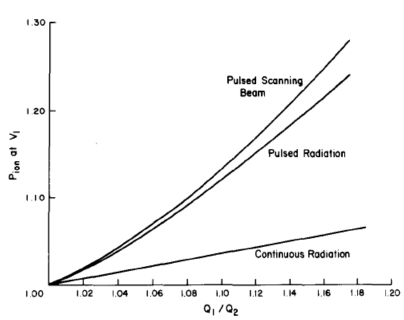


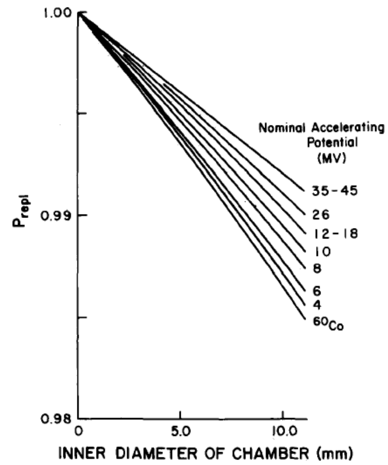
FIG. 4. Ionization recombination correction factors (P_{ion}) for continuous radiation (^{60}Co, Van de Graaff), pulsed radiation (accelerator-produced x rays and electron beams broadened by scattering foils), and pulsed scanning beams (magnetically scanned electron beams). These data are only applicable when $V_1 = 2V_2$.

Ion Recombination

- The measured dose will too small if all the charge in the ionization chamber is not collected
- A correction is required for ions that recombine
- To determine this factor, two sets of measurements are taken:
  - *Full bias applied (300V)*
  - *Half bias applied (150V)*

TG-21 Calibration

$$D_{\text{med}} = M\, N_{\text{gas}} (\overline{L}/\rho)^{\text{med}}_{\text{gas}} P_{\text{ion}}\, P_{\text{repl}}\, P_{\text{wall}}$$



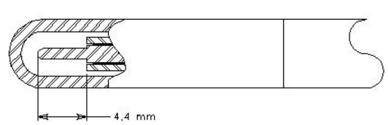
Replacement of Phantom Material with the Chamber

- Gradient corrections are required whenever the ionization chamber is at a location where the dose gradient has a nonzero slope and the magnitude of the correction increases with the slope as well as with the inner radius of the chamber
- It is generally accepted that corrections for perturbation of the electron fluence are required whenever the ionization chamber is at a location where charged-particle equilibrium has not been established

TG-21 Calibration

$$D_{\text{med}} = M\, N_{\text{gas}} (\overline{L}/\rho)^{\text{med}}_{\text{gas}} P_{\text{ion}}\, P_{\text{repl}}\, P_{\text{wall}}$$

$$P_{\text{wall}} = \frac{[\alpha(\overline{L}/\rho)^{\text{wall}}_{\text{air}}(\overline{\mu}_{\text{en}}/\rho)^{\text{med}}_{\text{wall}} + (1-\alpha)(\overline{L}/\rho)^{\text{med}}_{\text{air}}]}{(\overline{L}/\rho)^{\text{med}}_{\text{air}}}$$



Wall Correction Factor

- P_{wall} is a correction factor that accounts for the difference between the composition of the chamber wall and the phantom
- For photons, this factor depends on the beam energy, the wall thickness, wall composition, and fraction of the cavity ionizations contributed by electrons originating in the wall
- P_{wall} close to 1 for Farmer chambers, electron calibrations, and photon energies ≥6 MV

Questions

THOMPSON CANCER SURVIVAL CENTER

THE UNIVERSITY of TENNESSEE