Measurement of Ionizing Radiation

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1 Introduction

In the early days of x-ray usage for diagnosis and therapy, attempts were made to measure ionizing radiation on the basis of chemical and biologic effects. For instance, radiation effects on photographic emulsions, changes in the color of some chemical compounds, and reddening of the human skin could be related to the amount of radiation absorbed. However, these effects were poorly understood at the time and could only provide a crude estimation of radiation dose.

For example, in radiotherapy, a unit called skin erythema dose (SED) was defined as that amount of x- or γ -radiation that just produced reddening of the human skin. However, the unit has many drawbacks. Skin erythema depends on many conditions, such as the type of skin, the quality of radiation, the extent of skin exposed, dose fractionation (dose per fraction and interval between fractions), and differences between early and delayed skin reactions.

Although the SED was later discarded in favor of a more precisely measurable unit such as the roentgen, the skin erythema was used by physicians as an approximate index of response to the radiation treatments. This happened in the orthovoltage era when the skin was the limiting organ to the delivery of tumoricidal doses. The reliance on skin reaction for the assessment of radiation response had to be abandoned when megavoltage beams with the skin-sparing properties became the main tools of radiation therapy.

In 1928, the International Commission on Radiation Units and Measurements (ICRU) adopted the roentgen as the unit of measuring x- and g-radiation exposure. The unit is denoted by R. It may be mentioned at this point that the quantity exposure measured in R can be converted into a quantity called absorbed dose.

2 The Roentgen

The roentgen is a unit of exposure. The quantity exposure 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 (negatrons and positrons) liberated by photons in air of mass dm are completely stopped in air:

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

The SI unit for exposure is coulomb per kilogram (C/kg), but the special unit is roentgen (R):

 $1R = 2.58 \times 10^{-4} \text{ C/kg air.}$

The definition of roentgen is illustrated in Figure.



Diagram illustrating electronic equilibrium in a free-air chamber.

An x-ray beam in passing through air sets in motion electrons by photoelectric effect, Compton effect, or pair production. These high-speed electrons produce ionization along their tracks. Because of the electric field produced by the voltage applied across the ion-collection plates, the positive charges move toward the negative plate and the negative charges move toward the positive plate. This constitutes a current. The collected charge of either sign can be measured by an electrometer.

According to the definition of roentgen, the electrons produced by photons in a specified volume (shaded in above Fig.) must spend all their energies by ionization in air enclosed by the plates (region of ion collection) and the total ionic charge of either sign should be measured. However ,some electrons produced in the specified volume deposit their energy outside the region of ion collection and thus are not measured. On the other hand, electrons produced outside the specified volume may enter the ion-collecting region and produce ionization there. If the ionization loss is compensated by the ionization gained, a condition of electronic equilibrium exists. Under this condition, the definition of roentgen is effectively satisfied. This is the principle of the free-air ionization chamber, described below.

3 Free-Air Ionization Chamber

The free-air, or standard, ionization chamber is an instrument used in the measurement of exposure in roentgens according to its definition. Generally, such a primary standard is used only for the calibration of secondary instruments designed for field use. The free-air chamber installations are thus confined principally to some of the national standards laboratories.

A free-air chamber is represented schematically in the Figure.



An x-ray beam, originating from a focal spot S, is defined by the diaphragm D, and passes centrally between a pair of parallel plates. A high voltage (field strength of the order of 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 are made straight and perpendicular to the collector by a guard ring G. As discussed previously, electrons produced by the photon beam in the specified volume (shaded in the Fig.) must spend all their energy by ionization of air between the plates. Such a condition can exist only 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 (photon fluence per unit time) must remain constant across the length of the specified volume, and the separation between the diaphragm and the ion-collecting region must exceed the electron range in air.

If ΔQ is the charge collected in Coulombs and r is the density (kg/m³) of air, then the exposure X_p at the center of the specified volume (point P) is:

$$X_{\rm p} = \frac{\Delta Q}{\rho \cdot A_{\rm p} \cdot L} \cdot \frac{1}{2.58 \times 10^{-4}} \,\mathrm{R}$$

where A_p is the cross-sectional area (in meters squared) of the beam at point P and L (in meters) is the length of the collecting volume. In practice, it is more convenient to state the exposure (X) at the position of the diaphragm. Suppose f1 and f2 are the distances of the x-ray source to the diaphragm and point P, respectively. Because the intensities at point P and at the diaphragm are related by an inverse square law factor (f1/f2)², which also relates the area of the beams at the diaphragm and at point P, the exposure XD at the diaphragm is given by:

$$X_{\rm D} = \frac{\Delta Q}{\rho \cdot A_{\rm D} \cdot L} \cdot \frac{1}{2.58 \times 10^{-4}} \,\mathrm{R}$$

where A_D is the diaphragm aperture area.

Accurate measurements with a free-air ionization chamber require considerable care. A few corrections that are usually applied include (a) correction for air attenuation; (b) correction for recombination of ions; (c) correction for the effects of temperature, pressure, and humidity on the density of air; and (d) correction for ionization produced by scattered photons.

There are 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 the electrons liberated in air increases rapidly. This necessitates an increase in the separation of the plates to maintain electronic equilibrium. Too large a separation, however, creates problems of nonuniform electric field and greater ion recombination. Although the plate separation can be reduced by using air at high pressures, the problems still remain in regard to air attenuation, photon scatter, and reduction in the efficiency of ion collection. Because of these problems, there is an upper limit on the photon energy above which the roentgen cannot be accurately measured. This limit occurs at about 3 MeV. 10

4 Thimble Chambers

Free-air ionization chambers are too delicate and bulky for routine use. Their main function is in the standardizing laboratories where they can be used to calibrate field instruments such as a thimble chamber.

The principle of the thimble chamber is illustrated in the Figure. In Figure A, a spherical volume of air is shown with an air cavity at the center. Suppose this sphere of air is irradiated uniformly with a photon beam. Also, suppose that the distance between the outer sphere and the inner cavity is equal to the maximum range of electrons generated in air. If the number of electrons entering the cavity is the same as that leaving the cavity, electronic equilibrium exists.



Suppose also that we are able to measure the ionization charge produced in the cavity by the electrons liberated in the air surrounding the cavity. Then, by knowing the volume or mass of air inside the cavity, we can calculate the charge per unit mass or the beam exposure at the center of the cavity. Now if the air wall in Figure A is compressed into a solid shell as in Figure B, we get a thimble chamber. Although the thimble wall is solid, it is air equivalent (i.e., its effective atomic number is the same as that of air). In addition, the thickness of the thimble wall is such that the electronic equilibrium occurs inside the cavity, just as it did in Figure A. As before, it follows that the wall thickness must be equal to or greater than the maximum range of the electrons liberated in the thimble wall.

Since the density of the solid air-equivalent wall is much greater than that of free air, the thicknesses required for electronic equilibrium in the thimble chamber are considerably reduced.

For example, in the 100- to 250-kVp x-ray range, the wall thickness of the thimble (assuming unit density) is about 1 mm, and in the case of ⁶⁰Co γ rays (average $h\nu \approx 1.25$ MeV), it is approximately 5 mm. In practice, however, a thimble chamber is constructed with wall thicknesses of 1mm or less, and this is supplemented with close-fitting caps of Plexiglas or other plastic to bring the total wall thickness up to that needed for electronic equilibrium for the radiation in question. These "build-up" caps are required when making measurements in free air.

A. Chamber Wall

Figure C shows a typical thimble ionization chamber. The wall is shaped like a sewing thimble—hence the name. The inner surface of the thimble wall is coated by a special material to make it electrically conducting. This forms one electrode. The other electrode is a rod of low-atomic-number material such as graphite or aluminum held in the center of the thimble but electrically insulated from it. A suitable voltage is applied between the two electrodes to collect the ions produced in the air cavity.

As mentioned previously, most of the ionization produced in the cavity air is caused by electrons that are liberated in the surrounding wall (for at least up to 2 MeV photons) and enter the air cavity. Therefore, in order for the thimble chamber to be equivalent to a free-air chamber, the thimble wall should be air equivalent. This condition would ensure that the energy spectrum of electrons liberated in the thimble wall is similar to that in air.

For the thimble chamber to be air equivalent, the effective atomic number of the wall material and the central electrode must be such that the system as a whole behaves like a free-air chamber. The most commonly used wall materials are made either of graphite (carbon). Pakelite, or a plastic control on the inside by a

made either of graphite (carbon), Bakelite, or a plastic coated on the inside by a conducting layer of graphite or of a conducting mixture of Bakelite and graphite. The effective atomic number of the wall is generally a little less than that of air. It is closer to that of carbon (Z = 6). As a consequence, such a wall should give rise to less ionization in the air cavity than a free-air wall. However, the usually greater atomic number of the central electrode, its dimensions, and the placement geometry within the thimble can provide compensation for the lower atomic number of the wall.

B. Effective Atomic Number

It is instructive to discuss the term effective atomic number (Z') in greater detail. Z' is the atomic number of an element with which photons interact the same way as with the given composite material. Since photoelectric effect is highly Z dependent, Z' is considered for photoelectric interactions. Mayneord has defined the effective atomic number of a compound as follows:

$$\overline{Z} = \left(a_1 Z_1^{2.94} + a_2^{2.94} + a_3^{2.94} + \dots + a_n^{2.94}\right)^{\frac{1}{29}}$$

where $a_1, a_2, a_3, \ldots, a_n$ are the fractional contributions of each element to the total number of electrons in the mixture.

Example 1. Calculation of \overline{Z} for Air

Composition by weight: nitrogen 75.5%, oxygen 23.2%, and argon 1.3% Number of electrons/g of air: $\frac{N_{\Lambda}Z}{A_{w}} \times$ (fraction by weight)

Nitrogen =
$$\frac{6.02 \times 10^{23} \times 7}{14.007} \times 0.755 = 2.27 \times 10^{23}$$

Oxygen = $\frac{6.02 \times 10^{23} \times 8}{15.999} \times 0.232 = 0.7 \times 10^{23}$
Argon = $\frac{6.02 \times 10^{23} \times 18}{39.94} \times 0.013 = 0.04 \times 10^{23}$

Total number of electrons/g of air = 3.01×10^{23} (Table 5.1)

$$a_{1} \text{ for nitrogen} = \frac{2.27}{3.01} = 0.754$$
$$a_{2} \text{ for oxygen} = \frac{0.70}{3.01} = 0.233$$
$$a_{3} \text{ for argon} = \frac{0.04}{3.01} = 0.013$$

 $\overline{Z} = ((0.754) \times 7^{2.94} + (0.233) \times 8^{2.94} + (0.013) \times 18)^{1/2.94} = 7.67$

C. Chamber Calibration

A thimble chamber could be used directly to measure exposure if (a) it was air equivalent, (b) its cavity volume was accurately known, and (c) its wall thickness was sufficient to provide electronic equilibrium. Under the above conditions, the exposure X is given by:

 $X = \frac{Q}{\rho \cdot \nu} \cdot \frac{1}{A}$

where Q is the ionization charge liberated in the cavity air of density ρ and volume ν ; A is the fraction of the energy fluence transmitted through the air-equivalent wall of equilibrium thickness. The factor A is slightly less than 1.00 and is used here to calculate the exposure for the energy fluence that would exist at the point of measurement in the absence of the chamber.

There are practical difficulties in designing a chamber that would rigorously satisfy the conditions of above equation. It is almost impossible to construct a thimble chamber that is exactly air equivalent, although with a proper combination of wall material and the central electrode one can achieve acceptable air equivalence in a limited photon energy range. In addition, it is difficult to determine accurately the chamber volume directly. Therefore, in actual practice, the thimble chambers are always calibrated against a free-air chamber for x-rays up to a few hundred kilovolts. At higher energies (up to ⁶⁰Co γ rays), the thimble chambers are calibrated against a standard cavity chamber with nearly air-equivalent walls (e.g., graphite) and accurately known volume. In any case, the exposure calibration of a thimble chamber removes the need for knowing its cavity volume.

Although adequate wall thickness is necessary to achieve electronic equilibrium, the wall produces some attenuation of the photon flux.

When the wall thickness is much less than that required for equilibrium or maximum ionization, too few electrons are generated in the wall, and thus the chamber response is low. Beyond the equilibrium thickness, the chamber response is again reduced because of increased attenuation of the beam in the wall. The true exposure (without attenuation) can be obtained by extrapolating linearly the attenuation curve beyond the maximum back to zero thickness. If the chamber response is normalized to the maximum reading, then the extrapolated value for zero wall thickness gives the correction factor 1/A used in above equation. The correction for zero wall thickness, however, is usually allowed for in the exposure calibration of the chamber and is inherent in the calibration factor. Thus, when the calibration factor is applied to the chamber reading (corrected for changes in temperature and pressure of cavity air), it converts the value into true exposure in free air (without chamber). The exposure value thus obtained is free from the wall attenuation or the perturbing influence of the chamber.

D. Desirable Chamber Characteristics

A practical ion chamber for exposure measurement should have the following characteristics:

- 1. There should be minimal variation in sensitivity or exposure calibration factor over a wide range of photon energies.
- 2. There should be suitable volume to allow measurements for the expected range of exposures.

The sensitivity (charge measured per roentgen) is directly proportional to the chamber sensitive volume. For example, the reading obtained for a given exposure with a 30-cm³ chamber will be approximately 50 times higher than that obtained with a 0.6-cm³ chamber .However, the ratio may not be exactly 50, because a chamber response also depends on the chamber design, as discussed previously. 21

3. There should be minimal variation in sensitivity with the direction of incident radiation.

Although this kind of variation can be minimized in the design of the chamber, care is taken to use the chamber in the same configuration with respect to the beam as specified under chamber calibration conditions.

4. There should be minimal stem "leakage." A chamber is known to have stem leakage if it records ionization produced anywhere other than its sensitive volume. The problem of stem leakage is discussed later in this chapter.

5. The chamber should have been calibrated for exposure against a standard instrument for all radiation qualities for which exposure is to be measured.

6. There should be minimal ion recombination losses. If the chamber voltage is not high enough or regions of low electric field strength occur inside the chamber, such as in the vicinity of sharply concave surfaces or corners, ions may recombine before contributing to the measured charge. The problem becomes more severe with highintensity or pulsed beams. 22

5 Farmer Chambers

In the early days of radiotherapy, condenser chambers (e.g., Victoreen R meter) were most commonly used for measuring exposure rate in air for relatively lower-energy beams (≤ 2 MeV).

Although there were no basic limitations to their use for higher-energy radiation, the design of the stem and excessive stem leakage created dosimetric problems, especially when making measurements in phantoms. In 1955, Farmer designed a chamber that provided a stable and reliable secondary standard for x-rays and g rays for all energies in the therapeutic range. This chamber connected to a specific electrometer (to measure ionization charge) is known as the Baldwin-Farmer substandard dosimeter. The original design of the Farmer chamber was later modified by Aird and Farmer to provide better (flatter) energy response characteristics and more constancy of design from one chamber to another. This chamber is shown schematically in the figure.



Actual dimensions of the thimble and the central electrode are indicated on the diagram. The thimble wall is made of pure graphite and the central electrode is of pure aluminum. The insulator consists of polytrichlorofluoroethylene. The collecting volume (air cavity volume) of the chamber is nominally 0.6 cm3 (0.6 mL). There are three electrodes in a well-guarded ion chamber: the central electrode or the collector, the thimble wall, and the guard electrode. The collector electrode collects the ionization charge and delivers the current to a chargemeasuring device, an electrometer. The electrometer is provided with a dual polarity high-voltage source to hold the collector at a high bias voltage (e.g., 300) V). The thimble is at ground potential and the guard is kept at the same potential as 24 the collector.

The guard electrode serves two different purposes. One is to prevent the leakage current from the high-voltage electrode (the collector) and the other is to define the ion-collecting volume. Most often the collector is operated with a positive voltage to collect negative charge ,although either polarity should collect the same magnitude of ionization charge if the chamber is designed with minimal polarity effects.

Farmer chambers, like the one described above, and other Farmer-type chambers are commercially available. The latter chambers are constructed similar to the original Farmer chamber but vary with respect to the composition of the wall material or the central electrode. Examples include PTW, Capintec, NEL, Exradin, and others, each with several models and refinements. In general, the user is cautioned against using a chamber the characteristics of which have not been evaluated and found acceptable.

A. Components and Characteristics of Farmer-Type Chambers

Chamber wall: The thimble wall material of a Farmer-type chamber may be graphite or plastic such as PMMA (acrylic), nylon, A.E. (air-equivalent) plastic, and T.E. (tissue-equivalent) plastic. In the case of a plastic thimble, the inner surface of the wall is made conducting with a thin coating of graphite. The wall thickness of Farmer-type chambers varies between different makes and models. The approximate range is 0.04 to 0.09 g/cm².

Outer Electrode: The outer electrode is the thimble wall (if made of a conducting material) or the inner surface of the thimble wall coated with a conducting material.

Central Electrode: The central electrode consists of a thin aluminum rod of 1 mm diameter. It is the collector electrode that delivers the ionization current to a charge-measuring device, the electrometer.

Guard Electrode: A cylindrical conductor that wraps around the insulator surrounding the central electrode in the stem of the chamber. A second insulator wraps around the guard electrode, separating the guard from the outer electrode. The guard is kept at the same potential as the central electrode. Because there is no potential difference between the guard and the central electrode, any charge leakage does not get to the central electrode. The function of the guard is to reduce the leakage of any extraneous charge to the collecting electrode. The guard also passes ground loop and capacitive field noise currents away from the signal-carrying central electrode, significantly improving the signal to noise ratio.

Chamber (or cavity) volume: Because the thimble is vented to the outside, the cavity volume determines the mass of air in the cavity and, therefore, the sensitivity (charge measured/unit exposure) of the chamber. Farmer-type chambers have a cylindrical cavity with a nominal volume of 0.6 mL. The cavity radius is approximately 0.3 cm.

Energy dependence: Energy dependence (change in response/unit exposure with beam energy) for an ion chamber, in general, depends on the composition and thickness of the wall material.

Stem effect: The stem effect arises out of radiation-induced signal in the chamber stem and the cable, if exposed. The stem effect originating in the stem is directly related to the length of the unguarded stem. The amount of stem effect (originating either in the stem or the cable) is a function of energy as well as type of beam (photon or particle). Fully guarded Farmer-type chambers have almost immeasurable stem effect. However, the stem effect must be checked periodically. The stem correction may be determined as illustrated in the figure.



Measurements are made with the chamber oriented in each of the two positions shown. A number of points in the field are selected for such measurements and correction factors are obtained as a function of the stem length exposed in the field relative to the length of the stem exposed during calibration (e.g., 5 cm from the center of the chamber-sensitive volume, assuming that the chamber was calibrated at the center of a 10×10 -cm field).

6 Electrometers

Since the ionization current or charge to be measured can be very small, special electrometer circuits have been designed to measure it accurately. The most commonly used electrometers for ion chamber dosimetry are negative-feedback operational amplifiers.

A. Operational Amplifiers

Figure schematically shows three simplified circuits that are used to measure ionization in the integrate mode, rate mode, and direct-reading dosimeter mode.



The operational amplifier is designated as a triangle with two input points. The negative terminal is called the inverting terminal and the positive one is the noninverting position. This terminology implies that a negative voltage applied to the inverting terminal will give a positive amplified voltage and a positive voltage applied to the noninverting terminal will also give a positive amplified voltage. A negative feedback connection is provided, which contains either a capacitor or a resistor.

The operational amplifier has a high open-loop gain $(>10^4)$ and a high input impedance (>10¹² ohm). Because of this, the output voltage is dictated by the feedback element, independent of the open-loop gain, and the potential between the positive and negative inputs of the amplifier (called the error voltage) is maintained very low <100 mV). For example, if the ionization current is 10^{-8} A and the resistor in the feedback circuit of Figure B is 10⁹ ohm, the output voltage will be current times the resistance or 10 V. Assuming an open-loop gain of 10⁴, the error voltage between the input terminals of the amplifier will be 10^{-3} V or 1 mV.

This leads to a very stable operation, and the voltage across the feedback element can be accurately measured with the closed-loop gain of almost unity.

In the integrate mode (Fig. A), the charge Q collected by the ion chamber is deposited on the feedback capacitor C. The voltage V across C is read by a voltmeter and is given by Q/C, where C is the capacity. Measurement of this voltage is essentially the measurement of ionization charge. In the rate mode (Fig. B), the capacitor is replaced by a resistance R. Irradiation of the chamber causes an ionization current I to flow through the resistor, generating a voltage V = IR across the resistance. The measurement of this voltage reflects the magnitude of the ionization current. For total capacitative or resistive feedback circuits, the closed-loop gain of the operational amplifier is unity (i.e., the output voltage is given by the voltage across the feedback element). If a variable fraction of the output voltage is fed back to the input as by a voltage divider (Fig. C), the electrometer can be converted into a direct-exposure reading (R or R/min) instrument for a given chamber and a given quality of radiation.

7 Special Chambers

A cylindrical thimble chamber is most often used for exposure (or dose) calibration of radiation beams when the dose gradient across the chamber volume is minimal. It is not suitable for surface dose measurements. Highenergy photon beams exhibit a dose buildup effect, that is, a rapid increase of dose with depth in the first few millimeters. To measure the dose at a point in this buildup region or at the surface, the detector must be very thin along the direction of the beam so that there is no dose gradient across its sensitive volume. In addition, the chamber cavity must not significantly perturb the radiation field. Special chambers have been designed to achieve the above requirements.

A. Extrapolation Chamber

Failla designed an ionization chamber for measuring surface dose in an irradiated phantom in 1937. He called this chamber an extrapolation chamber as shown in Fig.



The beam enters through a thin foil window that is carbon coated on the inside to form the upper electrode. The lower or the collecting electrode is a small coinshaped region surrounded by a guard ring and is connected to an electrometer. The electrode spacing can be varied accurately by micrometer screws. By measuring the ionization per unit volume as a function of electrode spacing, one can estimate the incident dose by extrapolating the ionization curves to zero electrode spacing.

B. Plane-Parallel Chambers

Plane-parallel chambers (sometimes also called parallel-plate chambers) are similar to the extrapolation chambers except for the variable electrode spacing. The electrode spacing of the plane-parallel chambers is small (~2 mm) but fixed. A thin wall or window (e.g., foils of 0.01- to 0.03-mm-thick Mylar, polystyrene, or mica) allows measurements practically at the surface of a phantom without significant wall attenuation. By adding layers of phantom material on top of the chamber window, one can study the variation in dose as a function of depth, at shallow depths where cylindrical chambers are unsuitable because of their larger cavity volume. The small electrode spacing in a plane-parallel chamber minimizes cavity perturbations in the radiation field. This feature is especially important in the dosimetry of electron beams where cylindrical chambers may produce significant perturbations in the electron fluence due to the presence of their large air cavity.

The commonly used plane-parallel chambers (e.g., Markus, Holt, Capintec, Roos, Exradin ,and NACP) have a range of specifications with regard to sensitive volume, electrode spacing ,entrance window thickness, width of guard ring, and so on, depending upon their usage and desired accuracy.

For example, the Advanced Markus chamber (shown in Fig.) has a vented sensitive volume of 0.02 mL, electrode spacing of 1 mm, entrance window of 0.03 mm thick graphite-coated polyethylene membrane, guard ring of 2 mm width, and lower collector electrode of graphite-coated acrylic of diameter 5.4 mm. This chamber is waterproof when used with its protective acrylic cover of 0.87 mm thickness.



8 Ion Collection

A. Saturation

As the voltage difference between the electrodes of an ion chamber exposed to radiation is increased, the ionization current increases at first almost linearly and later more slowly. The ionization curve finally approaches a saturation value for the given exposure rate. The initial increase of ionization current with voltage is caused by incomplete ion collection at low voltages. The negative and the positive ions tend to recombine unless they are quickly separated by the electric field. This recombination can be minimized by increasing the field strength. If the voltage is increased much beyond saturation, the ions, accelerated by the electric field, can gain enough energy to produce ionization by collision with gas molecules. This results in a rapid multiplication of ions, and the current, once again, becomes strongly dependent on the applied voltage. The chamber should be used in the saturation region so that small changes in the voltage do not result in changes in the ionic current. 37

B. Collection Efficiency

As previously discussed, the maximum field that can be applied to the chamber is limited by the onset of ionization by collision. Depending on the chamber design and the ionization intensity ,a certain amount of ionization loss by recombination can be expected. Especially at very high ionization intensity, such as is possible in the case of pulsed beams, significant loss of charge by recombination may occur even at maximum possible chamber voltages. Under these conditions , the recombination losses may have to be accepted and the correction applied for these losses.

The collection efficiency, defined as the ratio of the number of ions collected to the number produced, may be determined either by calculation or by measurements.

Experimentally, the measured current is plotted against the inverse of the polarizing voltage in the region of losses below 5%. The "ideal" saturation current is then determined by linear interpolation of the curve to infinite polarizing voltage. Another, simpler, method, called the two-voltage testing technique, has been described by Boag and Currant for determining the efficiency of ion collection. In this method, measurements are made at two different voltages, one given working voltage and the other much lower voltage. By combining the two readings in accordance with the theoretical formula by Boag and Currant, one can obtain the collection efficiency at the given voltage.

9 Chamber Polarity Effects

It is sometimes found that for a given exposure the ionic charge collected by an ion chamber changes in magnitude as the polarity of the collecting voltage is reversed. There are many possible causes of such polarity effects, some of which have been reviewed by Boag. With the chamber operating under saturation conditions, major causes of the polarity effects include the following:

a. High-energy electrons such as Compton electrons ejected from the central electrode by highenergy photons constitute a current (also called the Compton current) independent of gas (cavity air) ionization. This may add to or reduce the collector current, depending on the polarity of the collecting electrode. In addition, some of these electrons may stop in the collector but may not be entirely balanced by ejection of recoil electrons from the collector .The above effects are minimized by making the collecting electrode very thin. Errors due to these causes are likely to be appreciable for parallel-plate chambers with small electrode spacing. However, the true ionization current in these cases can be determined by taking the mean of two currents obtained by reversing the chamber polarity. b. The Extracameral current collected outside the sensitive volume of the chamber may cause the polarity effect. Such a current may be collected at inadequately screened collector circuit points. Also, irradiation of the cable connecting the chamber with the electrometer can cause the extracameral current as well as the Compton current discussed above. The errors caused by these effects can be minimized but not eliminated by reversing the chamber polarity and taking the mean value of the collector current.

In general, the chamber polarity effects are relatively more severe for measurements in electron beams than photon beams, and in addition, the effect increases with decreasing electron energy.

Therefore, it is important to determine polarity effects of a chamber at various depths in a phantom. The polarity effect is very much dependent on chamber design and irradiation conditions.

10 Environmental Conditions

If the ion chamber is not sealed, its response is affected by air temperature and pressure. In fact, most chambers are unsealed and communicate to the outside atmosphere. Because the density of air depends on the temperature and pressure, in accordance with the gas laws ,the density of air in the chamber volume will likewise depend on these atmospheric conditions.

The density or the mass of air in the chamber volume will increase as the temperature decreases or pressure increases. Since exposure is given by the ionization charge collected per unit mass of air, the chamber reading for a given exposure will increase as the temperature decreases or as the pressure increases.

In the United States, the calibration laboratories [National Institute of Standards and Technology (NIST) and Accredited Dose Calibration Laboratories (ADCLs)] provide chamber calibration factors for reference environmental conditions of temperature $T_o = 22^{\circ}C$ and pressure $P_o = 760$ mmHg or 101.33 kilopascal (kPa) (1 atmosphere). The temperature and pressure correction, $P_{T,P}$, at different conditions is given by:

$$P_{T,P} = \left(\frac{760}{P}\right) \left(\frac{273.2 + T}{273.2 + 22.0}\right)$$
 (For *P* in mmHg)

or

$$P_{T,P} = \left(\frac{101.33}{P}\right) \left(\frac{273.2 + T}{273.2 + 22.0}\right)$$
 (For *P* in kPa)

Note: Temperatures in the above equations are converted to the absolute scale of temperature (in degrees Kelvin) by adding 273.2 to the Celsius temperatures.

11 Measurement of Exposure

Exposure in units of roentgen can be measured with a thimble chamber having an exposure calibration factor traceable to the NIST for a given quality of radiation. The chamber is held at the desired point of measurement in the same configuration as used in the chamber calibration (usually with its axis perpendicular to the beam axis). Precautions are taken to avoid media ,other than air, in the vicinity of the chamber that might scatter radiation. The chamber reading can be converted to exposure as follows:

 $X = M \cdot N_X \cdot P_{T,P} \cdot P_{ST} \cdot P_{ion}$

Where X is exposure in roentgens (R), M is the chamber reading (coulombs) measured under equilibrium conditions and corrected for any polarity effect, N_X is the chamber exposure calibration factor (R/coulomb) for the given quality beam, $P_{T,P}$ is the temperature and pressure correction, P_{ST} is the stem leakage correction, and P_{ion} is the ion recombination correction.