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Characteristics of radiation detectors for diagnostic radiology

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Abstract

The use of X-rays for diagnosis has been significant since its discovery. A measurement of the X-ray dose is the main determinant for risk vs benefit of these examinations. Radiation detectors are important for dose measurement. A description of these detectors, including the most frequently used ionization chamber, aids in the understanding necessary for their use. Proper and accurate use of detectors depends on an understanding of their calibration and their characteristics. Detectors such as ionization chamber, including specialized chambers, and solid detectors, including luminescent detectors, are described. This is followed by a description of the calibration process. The precision of measurements can be greatly affected by an understanding of the detector in use.

1. Introduction

Wilhelm Conrad Roentgen discovered X-rays over 100 years ago and revolutionized the practice of medicine. Research into the medical applications of X-rays was immediate and unceasing. That X-rays had detrimental effects in human tissue was recognized early, but relating the effects to the quantity of X-rays proved to be an intractable problem. In fact, radiation-induced erythema was one of the first means of measuring radiation exposure. In 1908 Paul-Ulrich Villard proposed that the ionization density generated in air under normal conditions of temperature and pressure be used as a standard for the measurement of radiation exposure. This concept was adopted in 1928 at the Second International Congress of Radiology which was held in Stockholm and has been used in radiation medicine since that time.

While exposure is conveniently measured using simple circuitry, the concentration of energy deposited in tissue, the absorbed dose, is the most direct indicator of the potential for biological changes that can adversely alter tissue structure and function. This is because absorbed dose is proportional to the concentration of ionization induced in tissue. For low linear energy transfer radiations, such as X-rays, absorbed dose is our standard indicator for biological risk. Nevertheless, because of the difficulty in measuring absorbed dose directly, it is usually inferred from exposure or some other signal generating mechanism and then derived using standardized techniques. This chapter describes devices used for exposure or dose measurements. The devices will be discussed in relation to their utility and calibration for an absolute measurement.

2. Relation of diagnostic radiological exposures to benefit and risk

2.1. Risk defined

Doses from diagnostic radiological exams are small and do not approach thresholds for deterministic effects. Nevertheless, the greatest source of exposure of the population to man-made ionizing radiation is from diagnostic radiology. Radiation-induced stochastic

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events, e.g. neoplasms or heritable effects, are therefore a concern. Additionally, interventional radiology frequently employs X-rays to help guide procedures. Doses from such procedures can exceed thresholds for deterministic effects.

To evaluate the potential radiation risk of a radiological procedure and to effect an appropriate risk-benefit of its use, it is necessary to know the absorbed dose to tissue (Wagner, 1991). According to Wagner et al. (1992) "with advances in our knowledge about risks from exposures to low levels of ionizing radiation, the need to accurately assess absorbed doses from diagnostic X-ray examinations has increased". This is perhaps most evident in screening mammography where an asymptomatic population of women is examined in order to detect that subset of individuals that has developed early breast cancer. Therefore, a large number of healthy women are repeatedly exposed to ionizing radiation.

2.2. Mammography: An example of benefit vs risk

Radiation dose and the characterization of mammography systems to provide good image quality has been a concern for quite some time (Wochos et al., 1978; Hammerstein et al., 1979; Stanton et al., 1984; DeWerd, 1988, 1990; Wagner et al., 1990). The radiation risk from mammographic screening has been estimated from BEIR V to have a 10 year minimum latency period (National Research Council, 1991). The background incidence of breast cancer (i.e. not radiation related) in the population of women undergoing screening increases with age at a much faster rate than the excess relative risk from mammographic screening. However, there is no evidence that a threshold for radiation-induced breast cancer exists, which advises that mammographic doses should be maintained at as low a level as is clinically acceptable for diagnosis. Since 1985, there has been an increase in the mean glandular dose because of the increased use of grids (Conway et al., 1994) and a trend toward increased film darkening which has resulted in increased image quality. Exposure measurements made with thermoluminescent dosimeters applied to the human breast show higher average exposures than those assessed from measurements with a standard 4.2 cm thick phantom (DeWerd and Chiu, 1993; Gentry and DeWerd, 1996), even when backscatter is taken into account. Fig. 1 shows that exposure increases uniformly with breast thickness with a correlation coefficient of 0.92. Maintaining a quality monitor on mammographic dose is therefore advisable.

Characterization of the mammography X-ray beam is based on measurements of exposure and half value layer (HVL), usually performed with ionization chambers (Wagner et al., 1990). To ensure the accuracy of these measurements, the calibration and the energy response of these chambers must be determined (see Diagnostic Detectors or Detectors Section). The calibration of diagnostic and mammography ionization chambers is a topic of great interest and has been investigated by the American Association of Physicists in Medicine (Wagner et al., 1992). The AAPM recommends in this report, that the precision of a mammographic ionization chamber be less than 1% (67% confidence limit). The AAPM also recommends that the chamber calibration vary less than 5% over the range of HVLs of 0.25 to 1.0 mm Al.

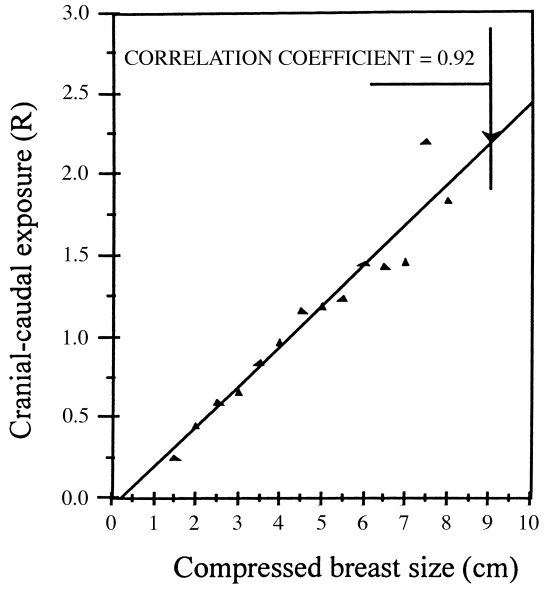


Fig. 1. Entrance skin exposure for a sample of 1431 compressed breast thickness of various types of fatty and glandular tissue (DeWerd and Chiu, 1993).

Average radiation absorbed dose to glandular tissue is the preferred measure of mammographic radiation risk. The mean glandular dose (MGD) is determined from the measurements of free-in-air entrance exposure and half-value-layer by application of a conversion factor computed from Monte Carlo simulations of X-ray photon transport in breast tissue (Barnes and Frey, 1991; Wu et al., 1991, 1994). There are uncertainties associated with the conversion factors because mathematical models are compared with a clinically compressed breast. The comparison of recent tables (Wu et al., 1991) with older ones in use during 1985 show differences from 3 to 10% (Conway et al., 1994). Conversion factors are sensitive to X-ray spectra (Servomaa and Tapiovaara, 1991) and depend on an accurate assessment of half-value layer (HVL). Unacceptable error in the measurement of HVL may occur if the energy response of the ionization chamber is excessive. The spectrum for the calibration of the

ionization chambers is thus important for the quantities determined from this table. The HVL and exposure measurement are affected by the X-ray spectra which consist of both characteristic lines and bremsstrahlung. The importance of mammographic spectra has been reviewed in *Medical Physics* (Jennings et al., 1981). If the calibration is inappropriate because of differences in the spectra, the resultant uncertainties in measurement of mean glandular dose are propagated to all patients receiving mammography throughout the United States. Measurements of spectra from diagnostic X-ray units and mammography units have been reported in the past (Fewell and Shuping, 1977, 1978a,b; Hawkins, 1981; Tucker et al., 1991).

3. Diagnostic detectors or dosimeters

Instruments used to generate a signal for the purpose of measuring exposure or dose are called dosimeters. A generalized definition of a dosimeter is a volume of medium sensitive to radiation, possibly surrounded by a wall of another medium. The sensitive volume is identified as a "cavity". The medium within the cavity can be gas, liquid or solid. Cavity theory defines the method of calculating the dose delivered using a detector of this description. Common detectors used in diagnostic radiology include the ionization chamber, film, thermoluminescent dosimeters (TLD), photostimulable luminescent dosimeters, scintillators and semiconductors. Each of these dosimeters have advantages and limitations. The dosimeter that has the greatest use and is traceable to NIST is the ionization chamber. However, the other dosimeters have found uses in specific areas.

3.1. Ionization chambers

3.1.1. General description of ionization chambers

In an ionization chamber an electric field is generated across two conducting plates whose separation defines a volume that is filled with a gas. The gas is usually air and the volume is often designed to communicate with the outside atmosphere, rendering the mass of air dependent on conditions of temperature, pressure and humidity. Humidity effects can be ignored but temperature and pressure effects can be significant. Some chambers are sealed from atmospheric communication to avoid this dependence. One plate of the ionization chamber is set to ground potential and the other at some voltage sufficient to collect all the ions that will be generated in the gas separating the plates but not so great as to accelerate the ions to speeds that will cause collision ionization of other molecules. The number of ions collected or the rate of their collection is the signal that is recorded. In theory, the exposure is

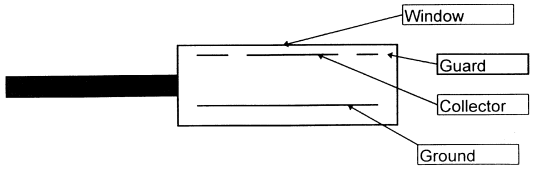


Fig. 2. Schematic of parallel plate type chamber.

the collected charge divided by the mass of air in the collection volume. In practice, a small correction factor will have to be applied to the reading because of physical limitations that cause inaccuracies. Correction factors should be obtained for all instruments used to calibrate an X-ray source. Calibration of the instrument usually involves the ionization chamber and the electrometer used to read the charge accumulated during the measurement by the chamber. ADCLs provide calibration for a number of different X-ray beam qualities.

The most common type of ionization chamber for diagnostic radiological measurement of exposure is a parallel plate chamber, as is shown schematically in Fig. 2. Parallel plate ionization chambers (also known as plane-parallel chambers) use two parallel, flat electrodes, separated by a few millimeters. They are calibrated with their plates oriented perpendicularly to the beam axis, which is also the orientation in which they should be used. The parallel plate type can be used as a model for a description of the essential elements of an ionization chamber.

Generally ionization chambers, as shown for the parallel plate chamber, have three electrodes, designated in Fig. 2 as the collector, the guard and the ground. The collector delivers the current to a device that registers the value of the current collected. The reading device, usually an electrometer or a charge digitizer, holds the guard and the collector at a suitable potential, usually +300 V. The guard keeps the field lines uniform and eliminates any signal from extraneous scatter, i.e. it better defines the collecting volume. Any ionization occurring in the air volume of the chamber has the positive ions and negative electrons pulled either to the collector or to the outer wall surface, which is normally at ground potential. Most often, the collector runs with a positive voltage to collect negative charge when measuring photons. The reading device generally gives an exposure value in Roentgens or a dose value (air kerma) measured in units of Gy. Measurement of air kerma using these chambers is achieved by multiplying the exposure value by the average energy required to produce an ion pair in dry air, which is 33.97 J/C or 8.76 mGy/R.

Other chamber constructions are used, the most common being a cylindrical design; Fig. 3 shows a schematic of a simple cylindrical chamber design.

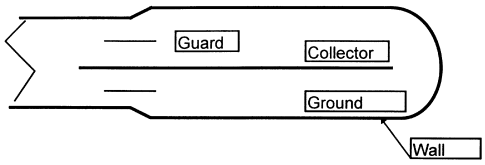


Fig. 3. Schematic of a cylindrical type chamber.

Spherical chambers are also made, generally being used for scatter measurements. The advantage of the cylindrical construction is that it overcomes the directional limitation of the parallel plate design. For example, it is clear from Fig. 2 that the parallel plate chamber is meant to be used with the plane of the window perpendicular to the direction of the X-ray beam. From the schematic of the cylindrical chamber (Fig. 3) it is equally clear that the chamber is uniformly sensitive in a cylindrical geometry.

3.1.2. Specialized ionization chambers

In addition to the general ionization chambers described above, there are ionization chambers designed for specialized uses. Two of these specialized chambers will be described here: the computed tomography (CT) chamber and the dose-area-product (DAP) meter.

3.1.2.1. Computed tomography (CT) chambers. A stretched out version of the cylindrical chamber of Fig. 4 results in an unique design of a cylindrical ionization chamber for computed tomography (CT). A CT chamber is often called a pencil chamber because its active volume is a thin cylinder about 100 mm in length. While most chambers are designed to be immersed in a uniform beam for proper measurement, the CT chamber is designed for non-uniform exposure from a single 360° scan of a CT unit. (Suzuki and Suzuki, 1978). Typically the chamber is inserted inside a phantom (usually also cylindrical in shape) that is used to attenuate the primary beam and to generate scattered X-rays, simulating conditions when a patient is in the field. For measurement of dose, the chamber is inserted lengthwise parallel to the axis of the phantom and parallel to the gantry axis. A thin (usually 10 mm or less) cross-sectional single 360° scan is made of the chamber-phantom unit about midway between the two ends of the chamber. Thus the primary beam is no more than about 10% of the full length of the chamber. However, because the exposure reading is comprised of the thin primary exposure and the scatter radiation it generates along the axis, it is possible to convert the reading into a dose from a multi-slice scan (Shope et al., 1981; Spokas, 1982). This unique use of the CT chamber requires that the response of the

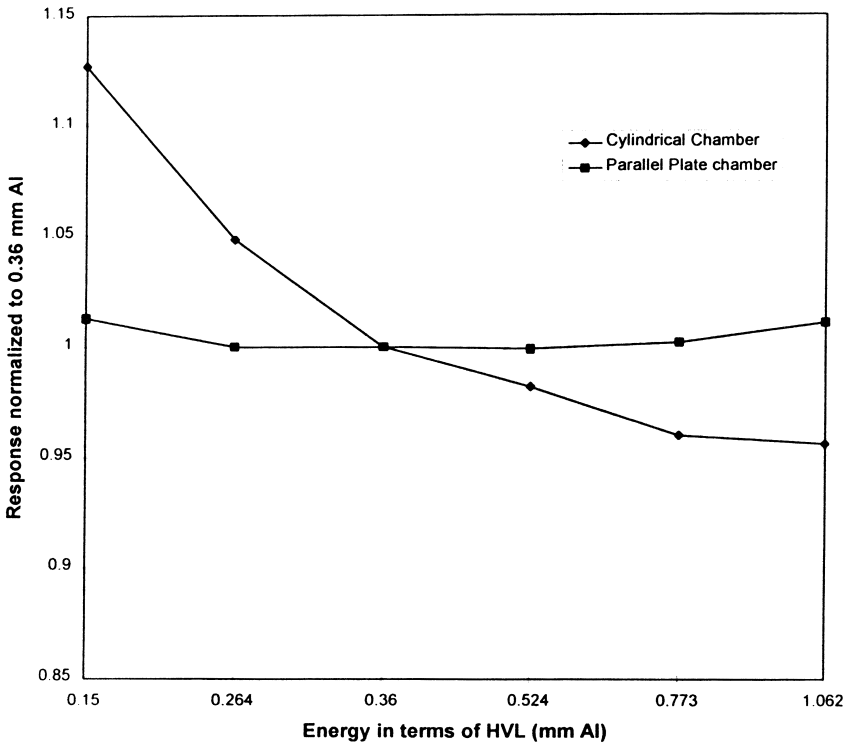


Fig. 4. Energy response of cylindrical chamber and parallel plate chamber in low energy region.

active volume be uniform along its entire axial length, a restriction that is not required of other cylindrical full-immersion chambers.

3.1.2.2. Dose-area-product (DAP) meters. Dose-area-product (DAP) meters are the dose in air (air kerma) or exposure-measuring devices that incorporate the area of the X-ray field into their reading. Sometimes these chambers have been called kerma-area-product (KAP) meters to distinguish that it is the dose to air or air kerma that is measured and not dose to tissue. The ionization chamber is much like the parallel plate chamber in design, except much larger. Its active area covers the entire radiation field. The actual measurement made is the integral of the exposure over the area of the X-ray beam. The calibration of such a device needs to include the ionization response and the correct beam area. The reading is the product of dose to air and the area of the X-ray field. The units are usually in mGy cm^2. This type of measurement yields a number that represents the linear deposition of energy by X-rays in the planar area. Dose, by itself, is the concentration of energy deposited in the small volume under consideration.

Dose-area-product meters are frequently used to monitor radiation usage in diagnostic and fluoroscopic examinations. Poorly collimated X-ray fields yield a greater value than well-collimated fields. A simple dose measurement is oblivious to the total area that is exposed. Therefore dose-area-product has the advantage that it provides a more accurate description of the overall stochastic risk. On the other hand, dose is the preferred descriptor for assessing the potential for deterministic risks, which is primarily related to the concentration of energy deposited in tissue.

Theoretically, dose-area-product meters can be positioned at any place along the beam path and still yield the same result. This is because dose decreases inversely with the square of the distance from the source and area increases with the square of the distance. Thus the inverse square relations exactly cancel. In practice, scatter radiation and other factors interfere with the theoretical result. Such meters are usually located at the collimator of an X-ray tube port to monitor radiation usage in diagnostic and fluoroscopic studies. Calibration of these devices is more complicated than the calibration of an ionization chamber. (Shrimpton and Wall, 1982; Gfirtner et al., 1997). The calibration of such a device needs to include the ionization response and the correct beam area.

3.1.3. The use and limitations of ionization chambers

Knowledge of the limitations of various ionization dosimeters are vital to their proper employment (Wagner et al., 1988). Their design specifications, such as exposure rate limitations, energy response, directional sensitivity, etc., must be carefully understood by the user and properly taken into account before accepting any exposure reading as valid. For example, if a chamber is sensitive to back scatter from a receptor, then the chamber will not be making a free in-air measurement unless it is not near a scattering material, such as the receptor.

Volume is another design property of ionization chambers that affects their use. In beams of conventional diagnostic intensities, about 1 R per second, volumes of a few milliliters are adequate for precise signal detection. When exposures at lower rates are measured, larger volumes are necessary for precise measurement. Volumes of about 100 ml and even 1000 ml and greater might be used in order to achieve appropriate levels of sensitivity, as for measurement of scatter radiation. One mistake frequently made by users is to assume that large volume chambers can be used to measure very low exposure rates by integrating readings over a long time. This is not necessarily so because all meters have limitations on exposure rate response, even when used in the integrating mode. Among other considerations, this limitation can be a result of the noise or leakage current being greater than the low exposure rate signal. On the other hand, larger volumes are not always appropriate in beams of conventional primary intensity either because of recombination effects or because the volume is physically too large for the measurement being made.

It is generally wise to calibrate your chamber over the energy region of use, since different chambers can show variations in energy dependence. As an example, Fig. 4 shows the energy dependence of two chambers for the low energy region (mammography energies), one a cylindrical design with a thick wall and the other a parallel plate design with a thin window (Coletti, 1995). Note that the measurement of half value layer would yield different results for the same X-ray beam depending on the chamber that was used.

The use of ionization chambers for the measurement of ionizing radiation for diagnostic radiology requires correct setup so that a free in air measurement is performed (Ng et al., 1997). The chamber and electrometer (or charge measuring device) both need to be calibrated. Generally they are calibrated as a system; if the chamber and electrometer are calibrated individually, the system factor, SF, is the product of the electrometer factor, EF, and the chamber factor, N_x. Calibration factors for the energy range of use should be obtained for each chamber, since chambers can differ in their energy response (See Fig. 4). Generally for diagnostic radiology applications, the appropriate energies are 80 to 120 kVp or half value layers of 3 to 7 mm Al. It is also important to measure the temperature and pressure at the time of measurement, unless your chamber is sealed to the atmosphere or if the

electrometer device automatically corrects for this effect. If there is a correction, it is wise to check if the correction is being made in a correct fashion. After the measurement, M, is made, the exposure, X, is obtained from the following equation, assuming a correction for temperature in Celsius, T, and pressure in mm Hg, P, is necessary to be made.

$$X = M^{*} SF\left(\frac{T+273.15}{295.15}\right)\left(\frac{760}{P}\right)$$

where SF is the system calibration factor, consisting of the N_x for the given energy calibration of the ionization chamber and the electrometer factor, EF.

3.2. Solid detectors

The primary advantage of the ionization chamber as a dosimeter device is that the mechanism for signal generation is identical to that of the quantity being measured, i.e. exposure or charge per kilogram. However, as with any instrument, its practical design places limits on its performance across the wide spectrum of conditions under which it is used. There exists no unique property of an ionization chamber that prohibits the use of other mechanisms for signal generation in dosimetry. A wide variety of alternative dosimeters exists, providing a versatile utility that is difficult to achieve with air-ionization exposure meters.

Alternative devices include film, thermoluminescent dosimeters, photostimulable luminescent dosimeters, scintillators and semiconductive devices. The method of calibration of these dosimeters is conducted in a manner similar to that of the air-ionization meter. Traditionally the disadvantages of these alternative devices have been poor precision of measurement, an energy-dependent response that differs considerably from that of air ionization and directional sensitivity (which also may be a problem with ionization chambers). Real-time dose measurements for patients may be conveniently accomplished with small dosimeters such as semiconducting devices, TLDs, or scintillators. Semiconductors and scintillators give results almost instantaneously, as compared to TLD that require reading in a separate device.

Since atoms of solids are relatively immobile within the material, the mechanism for signal generation by these materials is different from that of an air-ionization meter. In solids, the energy levels of outer, or valence, electrons of an atom cannot be associated with a single atom or molecule but are associated with the matrix of atoms and molecules that make up the solid. The energy levels of these outer electrons tend to organize themselves into bands of energy levels separated by gaps or "forbidden" zones. In the conducting band electrons are free to flow under the influence of an electric field. Electrons must be moved from the valence band to the conducting band before current flows. Some materials have trapping energy levels that lie between the valence and conducting levels. Trapped electrons can reside for a long time in these levels. Since energy must be imparted to elevate electrons from the valence level to the trapped level, these traps can be used to store information about a radiation exposure. In conductors, the valence and conducting bands overlap and outer electrons are free to move under the influence of an electric field. In insulators the conducting and valence bands are separated by gaps large enough to keep the conducting band depleted at normal temperatures. That is, the valence electrons are sufficiently bound to the matrix that they do not move under the influence of an electric field. In semiconductors, thermal energy is sufficient to ensure a continual supply of valence electrons that are moved to the conducting band, rendering the material semiconductive. The properties of semiconducting materials can be altered by doping them with agents that increase valence electrons (n-type) or decrease them (p-type). Interfacing semiconductors of different doping types produces solid state electronic devices such as diodes.

When X-rays interact in solid materials, electrons are liberated altering the populations of electrons in various energy levels. This alteration results in changes that can be detected using various methods that depend on the physical composition of the manufactured material. A familiar example is film wherein silver bromide crystals of a few micrometers diameter are distributed in a photographic emulsion. X-rays that interact in a crystal move a sufficient number of electrons that some of the silver ions in the crystal lattice are converted into silver atoms. The presence of these silver atoms in the crystal heightens the sensitivity of that one crystal to chemical photographic processing. The more silver bromide crystals that are sensitized by X-rays, the darker the film will be upon processing. This mechanism has a long history of use in dosimetry, as for example in personnel monitoring. The energy dependence of film as a dosimeter is compensated by employing attenuation filters in the radiation badge holder. While film is a widely used dosimetry device, it requires considerable perseverance to maintain acceptable reproducibility of the entire process, including uniform film sensitivity, chemical processing and optical density readout.

Calibration of solid detectors is done in a manner similar to that of air-ionization exposure meters. However, calibration at an ADCL is not usually acquired for reasons that might be related to precision of the devices, the fact that they might be disposable devices, or that the accuracy of measurement is not stringent. In these cases calibration against a properly

calibrated field-class instrument may be adequate. If such devices are used to "calibrate" X-ray sources, calibration of the dosimeter at an ADCL is highly recommended.

3.3. Luminescent dosimeters

Luminescence has found great use in dosimetry and a number of books and articles have been written about the process (Schulman and Compton, 1962; Cameron et al., 1968; Fowler, 1968; DeWerd and Stoebe, 1972; DeWerd et al., 1976; Braunlich, 1979; McKinlay, 1981; Horowitz, 1984; Hufton, 1984; Mahesh et al., 1989; McKeever et al., 1993). Luminescent dosimeters make use of the electron storage property of impurities in some solids such as alkali halides, e.g. LiF. Ionizing radiation excites electrons from the valence band to the conduction band wherein the electron migrates, often getting trapped in an appropriate electron trap impurity. A parallel description can be made for holes (positively charged); in this case, the holes would migrate in the valence band to the appropriate impurity. These trapped electrons remain at the impurity atom site until they are excited in some manner. If this excitation takes the form of light stimulation, the process is called photostimulated luminescence. If the method of excitation is heat, then the process is called thermoluminescence. When the crystal is excited by heat or light, the electrons are excited to the conduction band where they migrate to recombine with a hole. This may be in the valence band or via an impurity which has a hole trapped in it. The energy released is in the form of light photons. If the recombination occurred in an impurity acting as a recombination center, the luminescence is then characteristic of the energy states of this impurity.

Over a large range of doses, 0.1 mGy to 10 Gy, the crystals emit light in direct proportion to the absorbed dose of the dosimeter. Some materials, such as LiF:Mg, Ti have a linear response to the dose up to a limit, e.g. 10 Gy, and then have a greater than linear response, called supralinearity, up to 1000 Gy after which the response saturates. The onset of this supralinearity is dependent on another impurity, namely the hydroxide ion (Stoebe and DeWerd, 1985).

Thermoluminescent dosimeters can come in various forms, from powder (crushed crystals) to solid forms, usually extruded or embedded in some matrix. It is rare that a crystal would be used since there is such variation in impurity concentration along the length of the boule. Generally the TL sensitivity is proportional to the mass of the active phosphor present.

The annealing regime can affect the dose measurement. This is the method used to deplete the population of trapped electrons or to change the trap structure to prepare the material for reuse. Some TL materials have specified annealing regimes to eliminate low temperature glow peaks without affecting the higher temperature peak. This can be accomplished by a low temperature preheat before reading which removes electrons from low temperature traps while having an insignificant effect on the high temperature traps; this is the basis of the 100°C anneal before readout in LiF:Mg, Ti. Alternatively the low temperature trap structure can be rearranged (the dipole trap structure becomes three dipoles associated together) by an annealing at 80°C for 24 h. In this case, the low temperature trap structure no longer exists and so electrons are only trapped in the high temperature traps. Thus, upon readout only the high temperature trapped electrons give a thermoluminescent glow peak. The electrons in the traps are slowly affected by sitting at room temperature as well. This is called fading. This occurs after the material is irradiated and left to sit at room temperature. In LiF:Mg, Ti for example, the main dosimetry peak, peak 5, decreases only about 1% per year at room temperature; it has a half life of about 80 years. (Zimmerman et al., 1966) This means that the main dosimetry peak decreases only about 1% per year. However, the lower temperature peaks decrease much more quickly; peak 2 for example has a half life of about 10 h at room temperature. Thus, if these low temperature peaks are present, significant thermal fading can occur and affect the TL readout. In addition to thermal effects, light can also cause fading. Depending on the energy of the light and the defect center electron trap, the higher temperature traps can be affected if they are exposed to light while they are being stored.

The luminescent dosimeter measures X-ray response of the luminescent material which is based on the absorption of the X-rays in that material. What is of interest is the dose to air, water or tissue, since each of these can be related to clinically useful doses. Therefore, the measurement of the luminescent dosimeter must be converted to the dose in the desired material, e.g. air, water or tissue. For a given radiation beam, this problem can be side-stepped by calibrating the dosimeter in a beam of that type, itself already calibrated through some other means. The use of TLD involves the use of great care, precise repeatability and similarity in treatment from time to time. The greatest problems in accuracy and precision occur when the TLDs are treated in a different manner from time to time. Because TLD give large signals from small dosimeters, they often form the dosimeter of choice for *in-vivo* measurements in patients. The TLD is unobtrusive and its size makes it convenient for use on the body (Wochos et al., 1978).

3.4. Semiconductor devices

The simplest of semiconducting devices is the diode, manufactured by interfacing a p-type semiconductor with a n-type semiconductor. When an external voltage is applied across the two components with the positive potential at the p-type and the negative potential at the n-type, conduction occurs across the junction. If the voltage is reversed, holes migrate away from the junction in the p-type and electrons migrate away in the n-type, rendering the junction nonconductive, except for a small junction leakage current. As ionizing radiation strikes the semiconductor, electron–hole pairs are induced. This causes the junction to become conductive and the current increases with the rate of ion production. The size of the signal generated depends on the ionizing properties of the radiation and on its ability to penetrate to the junction. The amount of ionization reaching the junction may also depend on the cross-sectional area of the junction in relation to the incidence of the beam. Thus there may be some energy dependence and some directional sensitivity to these devices. Ceasing irradiation terminates the ion production and the diode recovers to its original state, except for any permanent alteration in the structural properties of the semiconductor boundary. Such alterations will depend on the amount of radiation exposure and the type of materials that comprise the semiconducting device. Diodes produce large signals from modest amounts of radiation, and can be made very small. The small size provides good spatial resolution at good sensitivity.

Semiconductor diodes can be operated without external bias, in the so-called photovoltaic mode, where the intrinsic depletion region is used to produce charge flow (Klevenhagen, 1977; Maruhashi, 1977). The charge flow is by impurity carrier in the diode junction and large instantaneous doses or dose rates produce a non-linear dose response in n-Si diodes (Rikner and Grusell, 1987). Using p-Si diodes reduces this effect (Grusell and Rikner, 1986).

The sensitivity per unit absorbed dose varies with the magnitude of previous exposure due to lattice damage (Knoll, 1989). The technique to account for the variation in sensitivity is simply to measure the conducting properties of the semiconductor prior to exposure and then to measure them after exposure. The degree of change is related to the dose. However, calibration of such devices must proceed with care since the degree of change may depend on the radiation exposure history of the device. Precision of measurement also appears to depend on radiation exposure history.

Another semiconducting device is the MOSFET, which stands for metal oxide semiconductor field effect transistor. MOSFET devices are specialized dosimeters of this semiconducting type. However, they are useful at high doses, greater than 0.1 Gy, and may have limited applications to fluoroscopic guided interventional radiological applications (Geise and O'Dea, 1998).

3.5. Scintillation detectors

Small scintillating phosphors are now available for use in monitor dose to patients from diagnostic procedures. A tiny phosphor (about the size of a small match tip) is bonded to a fiber optic cable. Typically, the scintillator is sealed in an opaque encasement whose inner surface is highly reflective to channel light from the phosphor to the fiber optic connection. Light is channeled through the cable to a light sensitive meter which is typically a photosensitive semiconductor. The radiation exposure is proportional to the intensity of the light signal. Calibration of such devices follows similar procedures as that of other solid detectors.

The process of scintillation has a similar mechanism to that of X-ray interactions in other solids. Generally, electrons are liberated by the interaction with X-rays. The liberated electrons distribute their energy by exciting other electrons creating a cascade of electron–hole pairs. Upon recombination of electrons with holes light is emitted. There is a considerable amount of nonradiative emissions and therefore not all the energy is converted into light.

Again precautions are necessary in the use of these dosimeters. The preservation of light generation is essential to the reliability of such scintillation detectors. Losses of light due to changes in integrity of connection at any of the transfer points from phosphor to readout will cause errors in measurement. Damage to the cable, caused for example by kinking, will render errors. If the fiber optic cable is coiled, a coil that is too tight will cause light transmission losses in route to the readout device. Scintillator dosimeters are susceptible to energy dependent responses, directional sensitivities and potential rate dependencies as are other detectors and attention to these details are necessary before using such devices.

4. Detector calibration

In the calculation of dose to a patient from a source, the accuracy of the chamber calibration forms the first step in the train of events that determines the final accuracy. Care must be taken in the measurement of the radiation source; however, the starting point is the calibration of the ionization chamber which is usually performed at an Accredited Dosimetry Calibration Laboratory (ADCL). These secondary calibration laboratories are directly traceable to national absolute

standards maintained at the National Institutes of Standards and Technology (NIST).

4.1. Understanding calibration

A great deal of confusion exists in the use of the term calibration. Most ionization chambers require calibration through comparison with a standard before their readings give an accurate value for the quantity measured. Calibration of ionization chambers means that their signal can be corrected to provide a value that is referenced back to primary standards maintained at a national laboratory or in the United States this national laboratory is NIST. Secondary calibration laboratories, such as an ADCL, maintain direct traceability to NIST by having their reference chambers, i.e. those chambers that are used to calibrate a users instrument, calibrated at NIST. During calibration of a users field-class ionization chamber, these secondary laboratories establish a factor for the users instrument that converts its signal into the value traceable to the national standard. However, due to the propagation of errors in transferring correction factors from one chamber to another, the uncertainty in the measurement made with a field class dosimeter will be greater than that of the chamber against which it was calibrated.

Calibration of an exposure meter is different than a calibration of the radiation source. In one case the ionization chamber, or other type of meter, is being calibrated so that its reading agrees with that of a standard; in the other, the source of radiation is being calibrated in terms of the exposure, air kerma, or absorbed dose produced by the radiation generating device. Another form of calibration is provided by manufacturers wherein they adjust the readout of dosimeters so that the dosimeters perform within given tolerances. This is not the same as an accredited calibration of the instrument because the uncertainties are greater. The multiple use of the term calibration results in a great deal of confusion. The definition of the term calibration does not distinguish between these uses. A differentiation needs to be made between a secondary laboratory calibration, a physicists calibration of the source and the "characterization" of an instrument or source as performed by industry.

Any instrument needs to have a quantitative determination made of its precision and accuracy. Precision is how reproducible an instrument is when multiple readings are made. Accuracy is how close an instrument reads to the absolute correct number, which is established by NIST or some other primary laboratory. Secondary laboratories transfer these numbers from NIST to the user with utmost care, maintaining uncertainties within tenths of a percent, if possible. A precise instrument is much preferred to an accurate instrument because a correction factor can be given to a precise instrument to make it accurate. A calibration from a secondary laboratory or NIST establishes this correction factor. The chain of calibration traceability from NIST through the ADCL to the clinic renders the calibration "traceable".

4.2. The free-air chamber

The primary standard for X-ray beams at NIST is obtained from a free-air chamber at X-ray energies. The free-air chamber (FAC) measures parameters that are directly involved in the definition of the roentgen (R), which in SI units is equal to 2.58×10^{-4} C/kg exactly. Since the FAC gives the desired quantity directly in Coulomb per kilogram of air, it falls into the class of an absolute dosimeter, as opposed to a secondary dosimeter. The measure of exposure, as shown earlier, is of the energy transfer of X-rays in air. The definition of exposure requires the measurement of all ionization produced by collision interactions in air by all electrons resulting from X-ray interactions in a known mass of air. A free-air ionization chamber is an ionization chamber with a thickness of air between the beam and the wall that exceeds the range of secondary electrons created by the X-ray beam, so none of the secondary electrons terminate prematurely by colliding with a wall. At low X-ray energies the range of the secondary electrons in air is only a few centimeters. Therefore a chamber of practical size can be designed to collect all such secondary electrons and measure the absolute in-air exposure. For these low energies, ionization chambers can be compared directly with a free-air chamber for the primary calibration. These primary measurements are then transferred to the ADCL which then transfers the calibration to the clinic. The uncertainty increases at each step, but the physicist at the clinic can expect the uncertainty in the calibration factor to remain within 3% (95% confidence limit).

4.3. Example of a free-air chamber

A number of different designs of free-air ionization chambers have evolved, some plane-parallel and some cylindrical in geometry. An Attix style variable length free-air ionization chamber for energies up to 50 kVp (Coletti et al., 1995; Coletti, 1995) will be described here being illustrative of the measurement. Attix proposed the first design for this novel free-air ionization chamber with a variable-length in 1961 at the United States Naval Research Laboratory (Attix, 1961). This chamber consists of two telescoping cylinders with the X-ray beam passing along their axis through holes at the centers of the two flat ends (see schematic of fully extended chamber in Fig. 2). The X-ray beam is defined by passing through an aperture of known

cross-sectional area A_0 in a fixed diaphragm, aligned with the chamber axis. Ions formed throughout the collecting volume are collected on an off-center telescoping electrode operated at ground potential. The chamber shell is held at high potential. An insulator is fixed around the chamber for electrical safety. The diameter of the collecting rod is such that only a small ($<0.01\%$) loss of ionization results from electrons striking it. The chamber is designed such that in its collapsed condition, secondary electrons originating in the X-ray beam at the fixed central plane of the chamber cannot reach the chamber walls in any direction. An important correction at very low energies is for the attenuation of the X-ray beam between the collector center and the defining plane of the entrance aperture. The linear attenuation coefficient at 20 keV in air is $\sim 10^{-3}$/cm and accounts for a correction of about 2%. The Attix FAC can easily measure this quantity by changing the center position but not the volume.

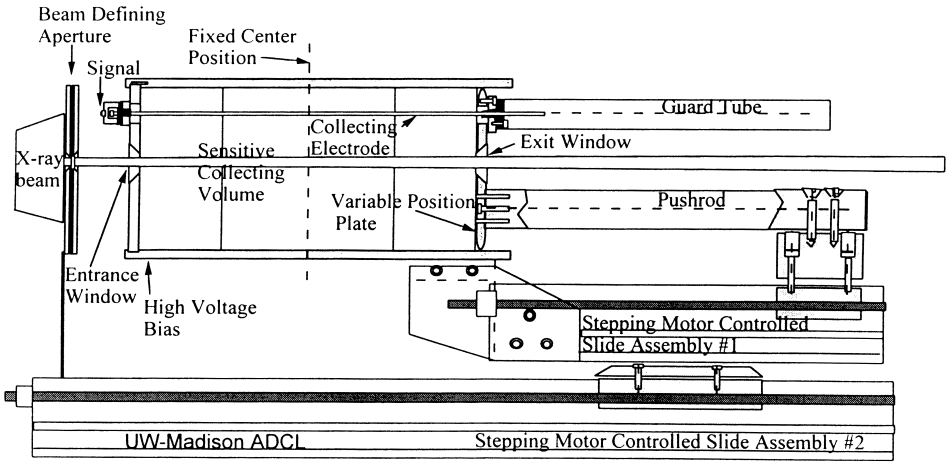
A standard free-air ionization chamber satisfies the operational definition of the quantity known as exposure (or air kerma), eliminating any energy dependence, which would be characteristic of walled ion chamber construction. The Attix free-air chamber has the advantages that it has no measurement dependence due to charged particle disequilibrium; little need for uniformity of the electric field, plate alignment or the maintenance of the collector at ground; and the mass of the irradiated air can be accurately defined. This last point is the most significant since it provides a measurement of the basic definition of exposure (ionization per unit mass of air) or air kerma and thus a standards laboratory equivalent calibration of the X-ray beam and the ionization chambers. The uncertainty in the collection volume in conventional free-air chambers is eliminated in the variable length Attix free-air chamber (Attix, 1961) because the change in volume can be determined via a precision screw mechanism (see Fig. 5). Thus, a precise and accurate definition of the air mass is accomplished by precisely varying the volume by means of precisely varying the length.

At a minimum, two measurements are made with the Attix free-air ionization chamber for a measurement of exposure. An ionization measurement is made at an arbitrary volume, using an associated electrometer. The chamber volume is then expanded (or contracted) by a precisely known change in length ΔL, keeping the chamber midplane and the defining aperture fixed relative to the X-ray tube focus. A second ionization measurement is made. The observed increase (or decrease) in charge collected is due only to the electrons that originate in the incremental volume in the center of the chamber defined by ΔL. Those electrons will deposit all of their energy in the confined volume of the chamber and produce their full complement of ionization that will be measured in accordance with the definition of exposure.

If A_0 is the area of the aperture (m^2), ΔL is the length of chamber expansion (m) and ρ is the air density (kg/m^3), then the exposure at the aperture is given by:

$$X = \frac{\Delta Q}{\rho A_0 \Delta L} e^{\mu x'} (1 - f_s + f_e) \quad [C/kg]$$

where x' is the distance from the aperture to the fixed central plane, m is the narrow beam attenuation coefficient for the X-rays in air, f_s the fraction of ΔQ that is produced by scattered and bremsstrahlung rays and f_e



(a) Chamber fully extended

Fig. 5. Schematic of the Attix variable length free-air chamber shown fully extended (Coletti et al., 1995).

the fraction lost to any electrons being stopped by the collecting rod and inadequate chamber radius. When the UW (University of Wisconsin) Attix free-air ionization chamber was directly compared with the NIST Ritz 20–100 kV free-air-chamber with tungsten anode–aluminum filter and molybdenum anode–molybdenum filter X-ray beams up to 50 kVp, both free air chambers agreed to within 0.5%, which is within the limit of the uncertainty involved in this comparison (Coletti et al., 1997). The absolute determination of exposure (in Roentgens) can therefore be made to an accuracy somewhat better than 0.5%.

With the aid of this free air chamber, the NIST Ionizing Radiation Physics Laboratory has recently set up a calibration range for mammographic molybdenum X-ray beam qualities. Therefore for any ionization chamber, the calibration laboratory provides calibration factors, N_x, that give the exposure per unit reading on the chamber, and N_k, that give the air-kerma at a meter per unit reading based upon the NIST absolute measurement with the free air chamber.

5. Summary

It should be evident to the reader that a knowledge of the characteristics of the dosimeter used for diagnostic radiology measurements is very important. The ionization chamber is the main device used for these measurements but it is important to realize that other devices have specially useful applications. In each case there are characteristics involved in the response of the dosimeters that need to be considered so that accurate and precise measurements can be achieved.

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