Journal of Radiotherapy in Practice

Journal of Radiotherapy in Practice 2003
3, 69–76

Original Article

Review of surface dose detectors in radiotherapy

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Abstract

Several instruments have been used to measure absorbed radiation dose under non-electronic equilibrium conditions, such as in the build-up region or near the interface between two different media, including the surface.[1–6] Many of these detectors are discussed in this paper. A common method of measuring the absorbed dose distribution and electron contamination in the build-up region of high-energy beams for radiation therapy is by means of parallel-plate ionisation chambers.[1,7–9] Thermoluminescent dosimeters (TLDs), diodes and radiographic film have also been used to obtain surface dose measurements. The diamond detector was used recently by the author in an investigation on the effects of beam-modifying devices on skin dose[10] and it is also described in this report.

Keywords

Surface dosimetry; build-up dosimetry; detectors; ionisation chamber; diamond detector

BACKGROUND OF REVIEW

The absorbed dose at the surface of a patient or phantom irradiated with a beam of megavoltage X-rays arises from three components.[1,11–18] These are contributions from electrons generated in air above the phantom, from electron backscatter within the phantom, and from electrons generated by any solid material in the beam, such as the flattening filter, collimators and blocking tray. The amount of dose from contaminant electrons from the head of the linear accelerator depends strongly on clinical set-up parameters such as field size, SSD, energy, and beam-modifiers.[1,2,5,8,9,11–14,16,18–24] These contaminant electrons are the primary cause of skin dose increase.[1,11,16–18,24] Unfortunately physical data on surface dosimetry is rarely available due to the complexity of interface dosimetry, and the lack of emphasis until recently on the importance of minimising skin dose.[3,5,20,25] An understanding of the role of electron contamination in megavoltage therapy machines is required to characterise dosimetry in the build-up region. Consequently, the study of the exact skin dose and the development of methods to ensure that it is minimised is a logical step in the search for improvements of radiation methods to treat cancer and improve cosmesis. A review of detectors was undertaken in relation to performing surface and build-up dose measurements to determine the effect of beam-modifying devices on skin dose.[10] This review of detectors is presented in this paper.

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SURFACE DOSE DETECTORS

Ionisation chambers

In the surface region electronic equilibrium does not exist, as in all transition zones between two different media, and this will cause perturbation effects in ionisation chambers.[1,3,4,6,9,11,26,27] It has been demonstrated in the literature that the

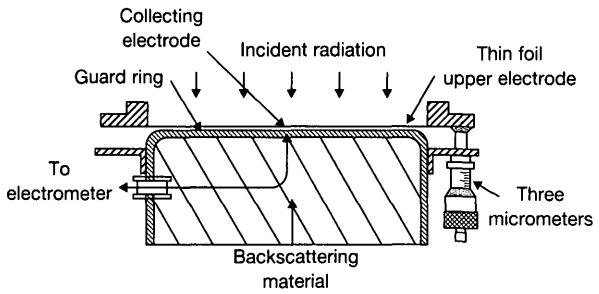

Figure 1. Extrapolation ion chamber.

instrument of choice is the extrapolation plane-parallel ionisation chamber because of its high accuracy in the non-electronic equilibrium region (Fig. 1).[1–4,6,26] The reason for this recommendation is that chambers of fixed volume will tend to indicate a larger dose in the build-up region than the actual dose.[3,4,6,26] This increase in measured dose is mainly a result of secondary electrons scattered into the chamber volume from the walls of the chamber.[3,4,7]

The beam enters the extrapolation chamber through a thin foil coated to form the upper electrode (Fig. 1). The lower or the collecting electrode is a small coin-shaped region surrounded by a guard ring and is connected to an electrometer. Micrometer screws can vary the electrode spacing accurately. By measuring the ionisation per unit volume as a function of electrode spacing, the superficial dose can be estimated by extrapolating the ionisation curves to zero electrode spacing.

The perturbation effects in parallel-plate ionisation chambers used for build-up measurements have been examined.[4] The fluence perturbation due to electrons emitted through the side-walls that cause an over-estimation of the surface dose, have been thoroughly investigated by measurements using film, extrapolation chambers, and by calculations.[2–4,9] The perturbation of the electron fluence in these build-up measurements is due to lack of equilibrium in the transport of different categories of electrons contributing to the ionisation in the chamber.[4] The main contribution to the ionisation, especially for small plate separations, is due to electrons coming from the air and treatment head, these electrons may then be backscattered. Photons hitting the chamber may emit electrons in the front electrode, collector and through the side-walls. These electrons may then be scattered into the chamber volume. Electrons hitting the phantom close to the chamber may be scattered into the chamber. A small contribution is also obtained from electrons produced by photon interactions in the chamber. The perturbation in the chamber is mainly due to these effects.[4,15,28]

The electron fluence varies with side-wall material and chamber geometry. In order to obtain a small perturbation effect, i.e. to reduce the contribution from side-wall electrons to facilitate an accurate extrapolation, the extrapolation chamber should have a large guard width compared to the electrode separation (chamber height) and the side-walls should have as large an angle as possible with the central axis. The side-wall should be made of the same material as the rest of the chamber so as to obtain a situation as homogenous as possible.[4] This indicates that parallel-plate chambers used for measurements in regions where electronic equilibrium does not exist should therefore also have sidewalls with a large angle to the central axis if a low perturbation effect is desired.

The measurement of build-up curves using an extrapolation chamber is a very laborious and time-consuming procedure, and few institutions have these instruments at their disposal.[1,3,6,9] Fixed-separation plane-parallel ionisation chambers, such as a *Markus*-type chamber, are more convenient to use in any instance and have therefore been used.[1,3,4,26] Measurements of relative surface dose and dose in the build-up region are generally carried out using thin-windowed ionisation chambers. Chambers used in published literature included the plane-parallel ionisation chambers or pancake chambers, such as the *Markus* chamber,[1,3,7,26,29,30] the *Capintec* chamber,[3,5,13,16,18,22,23,28] and the *Memorial* chamber[2,3,15,28,31]; the thimble chambers, such as the *Farmer* chamber[32–34] and the pinpoint chamber.[20] The ionisation chamber is able to accurately measure dose distributions for regions where the dose is not varying rapidly. The relatively large sensitive volume of most chambers means, however, that a significant spatial averaging, or smoothing, of the true dose distribution occurs. Ionisation chambers are therefore not suitable when high spatial resolution is required, such as in the accurate measurement of surface doses. The

use of very small ionisation chambers is precluded by the low density and hence low sensitivity, of their air volume.[35] New chamber designs such as the NACP chamber and the PTW "Advanced Markus" parallel-plate chamber are available although no published literature exists on their use for surface dose measurements.

Corrections for parallel-plate chambers

If surface dose measurements are made with parallel-plate chambers with fixed electrode distance, the perturbation effect will increase the ionisation in the chamber as stated. Ionisation values have to be corrected in order to take into account the fluence surface perturbation conditions. This perturbation depends on the volume and type of the chamber used, and the radiation energy.[4,7] Velkley et al's analytical formulae in 1975,[6] Mellenberg's over-response corrections in 1990,[26] and Gerbi and Kahn's corrections in 1990,[3] have been developed in order to correct the readings for various types of detectors in the build-up region. These correction procedures are based on the results of extrapolation chamber measurements.

Velkley et al.[6] developed a formula from their aluminium-walled extrapolation chamber measurements, for correcting results obtained in the build-up region with a finite size parallel-plate ionisation chamber, to zero plate separation, using a correction factor expressed as percentage correction per mm plate separation.

This method has been used by several authors.[2,4,5,8,9,36] Velkley et al's[6] correction factors were intended to be applicable to all types of fixed parallel-plate chambers. Velkley proposed that by applying the correction procedures outlined, build-up curves could be obtained with relative ease using a thin, fixed-volume, parallel-plate ionisation chamber. However, Nilsson and Montelius[4] showed that correction factors are specific to each chamber design and dependant upon chamber diameter, guard width, side-wall material, plate separation and volume. Applying correction factors, obtained with one extrapolation chamber for a specific parallel-plate chamber, to chambers of different design and composition can lead to significant errors.[3,4,26]

Mellenberg[26] determined the build-up region over-response correction in the Markus chamber, by comparing measurements made with the fixed volume parallel-plate (*Markus*) and extrapolation chamber. A *Markus*-type chamber is a fixed-volume parallel-plate chamber with an electrode separation of 2 mm. The Markus chamber has a measuring point of 0.023 mm, however when used at shallow depths the reading depends on the polarity used and all parallel-plate chambers over-respond at the surface. Because of their relatively large separation compared with the extrapolation chamber and their small guard ring, these parallel-plate chambers show an over-response in the build-up region and especially at the surface. This over-response decreases with increasing angle of incidence of the radiation beam to the detector.[3,15] Mellenberg[26] reported that the correction for over-response of parallel-plate chambers is essentially independent of field size but increases with decreasing energy. Mellenberg produced a complete set of over-response correction factors for the Markus-type chamber at several photon energies. These corrections may be applied to surface dose measurements from the *Markus* parallel-plate chamber by simple subtraction of the derived corrections. Kim et al.[1] applied over-response corrections in accordance with Mellenberg's work. According to Mellenberg's report,[26] an over-response correction of 13.8% and 10.7% (absolute) is applied at the surface for 4 MV and 6 MV photon beams respectively, for a *Markus*-type chamber. At only 2 mm depth, the over-response of the *Markus* chamber under investigation decreased to 50% of the surface over-response. These results are limited to basic types of measurements (i.e. unblocked fields at 100 cm SSD). However, application of these corrections to *Markus* chambers build-up measurements, allows build-up data to be acquired in a reasonable manner with similar results to those that are obtained with time-consuming extrapolation chamber measurements.[26]

Gerbi and Kahn[3] demonstrated that Velkley et al's correction did not produce acceptably accurate percentage depth dose values for all parallel-plate chambers in their research, and found that the *Markus* chamber over-indicated the percentage depth dose at the surface by more than 11% even after Velkley's correction was applied. They also found that Velkley et al's correction exaggerated

the amount of in-scatter at higher energy beams. Gerbi and Kahn[3] presented data for Co^{60}, 6, 10, 18, and 24 MV photon beams that show the magnitude of the over-response in the build-up region for four commercially available plane-parallel ionisation chambers – 2 *Memorial* pipe chambers, a *Markus* chamber and a *Capintec* chamber – versus results obtained using both an extrapolation chamber and Lithium Fluoride (LiF) Thermoluminescent dosimeters (TLDs). All chambers over-responded in the build-up region to some degree based on their internal dimensions. Differences greater than 19% in the percentage dose, at the surface of a phantom, were found for the *Markus* chambers for Co^{60}. At 6 MV, all the fixed-separation plane-parallel ionisation chambers over-responded at the phantom surface but to a lesser degree than at Co^{60} energies. The *Markus* chamber indicated a percentage depth dose at the surface that was more than 10% higher than that indicated by the extrapolation chamber. TLD chips, when placed directly on the phantom surface, also indicated a surface dose that was ~12% too high. The indicated percentage depth dose at the surface using TLD powder was within 3% of the dose measured with the extrapolation chamber for the four field sizes studied.

The magnitude of the over-response of the chambers in Gerbi and Kahn's study[3] was more severe at lower beam energies in agreement with the results of Velkley.[6] As beam energy increases, electron scattering from the side-walls of the chamber are less likely to reach the active volume of the chamber since electron scattering is more forward directed at higher beam energies. In Gerbi's work,[3] TLD chips also over-indicated the dose at the surface of the phantom for all beam energies. According to Gerbi and Kahn,[3] this occurs as the chips integrate dose over their total thickness, which in his study were 0.38 mm, and yielded a dose comparable to what would be measured at 0.2 mm depth. TLD chips' response approach the extrapolation chamber value, as beam energy increases, since there is less percentage change in dose per mm for higher beam energy, thus making the dose at 0.2 mm closer to the value at the surface. The surface percentage dose measured using a layer of TLD powder agrees very well with extrapolation chamber values for all energies investigated except Co^{60}, in Gerbi and Kahn's study.[3] For all plane-parallel chambers studied, the chamber over-response was greatest within the first 20% of the D_{max} depth. At greater depths, there was little difference between the percentage depth dose registered by the plane-parallel ionisation chamber and the extrapolation chamber.[2,3,26]

Gerbi and Kahn proposed a mathematical formula, in order to correct the readings for various types of detectors in the build-up region, obtained by comparing the readings of the various detectors with the readings of an extrapolation chamber. This expression quantifies the over-response of plane-parallel chambers in the build-up region, and accounts for chamber plate separation, the collector-side wall distance, and the beam energy. Gerbi and Kahn's correction has been used by many researchers.[7,13,20]

Bjarngard et al. 1995[11] described an experimental method to determine the dose near the surface using a mathematical extrapolation based on Monte Carlo-calculated kerma values to correct for electron disequilibrium near the surface.

Other Detectors

TLDs

TLDs have a useful role in the measurement of skin doses on patients or on anthropomorphic phantoms, where chambers have voltages applied. TLDs are safe in this regard. These dosimeters may be in the form of powder, impregnated plastic discs, chips or rods. The use of TLDs have been well reported.[3,9,34,37–41] TLDs have many disadvantages that rendered them unsuitable as detectors in the author's research on the effect of beam-modifying devices on surface dose.[10] They need to be calibrated frequently to increase measurement precision. TLD chips and TL powder must be in sealed containers when used in conjunction with a water phantom. TLD readings are obtained after irradiation, by placing the TLD material – lithium fluoride or lithium borate – in the "TLD Reader" where it is heated to very high temperatures – around 300°C in an oxygen-free (nitrogen) atmosphere. The light output is measured using a photomultiplier and amplifier feeding a digital display. Therefore, instantaneous results are not possible. The management

of a large number of results would be time-consuming with the delayed readings in comparison with instantaneous results from alternative dosimeters.

Diodes

Diodes have also been used in surface dosimetry.[8,34,42,43] Silicon diode detectors have the advantage of a small, high-density, sensitive volume and thus have high spatial resolution.[35] Diodes are encapsulated in a protective sheath. Similar to the TLDs, diodes have many disadvantages that rendered them unsuitable as detectors in the author's research.[10] Frequent calibrations are necessary to increase measurement precision for absolute dose measurement.[46] A significant disadvantage is the non-water-equivalence of the silicon, and thus diodes are energy dependent.[35,46]

Photographic film

Photographic film has also been used,[4,37,44,45] but this method suffers from several disadvantages. It is difficult to obtain reproducible and accurate results even though great care is taken to process films under standard and controlled conditions. For instance, variations of developer strength and temperature, and of processing techniques make great differences to the density. Films also show great differences in sensitivity to radiation.[46] Correction factors are necessary to take into account temperature effect, film post-irradiation colour stability with time, long-term instability of the imaging system and build-up effect depending on beam energy.[44] Two main types of film are available. Silver halide film is difficult to obtain accurate surface doses, as either the work must be completed in the dark or the film must be covered with an envelope that has finite thickness. This film has a higher energy response at low energy, which may affect the measured distribution in the build-up region. It is also not tissue equivalent. Gaf chromic film still has a high cost. It does not require wet processing, is more tissue equivalent than silver halide film and is not sensitive to white light. It requires a high radiation dose to achieve acceptable accuracy. Film has a thickness of 0.18 mm.

The diamond detector

There have been several reports on the characteristics of diamond detectors in dosimetry.[35,47–57] The diamond detector is typically used for dose measurements in high-energy photon and electron beams, where the fields are very small or have steep gradients. It is used for example in electron dosimetry,[35,51,55] radiosurgery,[35,47,53,54] brachytherapy[54] and in intensity modulated radiotherapy.[48–51] The diamond detector has the advantages of excellent spatial resolution, near water-equivalence, water resistance, high sensitivity, high resistance to radiation damage (no radiation damage up to 10^5 Gy), and nearly no directional dependence.[35,50,52,55,57,58] Curves measured with the diamond detector do not require an energy-dependent correction, as is required for ionisation chamber measurements.[35] The radiation sensitive region of the diamond detector is a low-impurity natural diamond with a thickness of 0.33 mm.[35,55] It has a sensitive volume of 1.4 mm^3 and a sensitive area of 4.3 mm^2.[35,55] The diamond is located at a distance of 1 mm from the top of the polystyrene cylindrical detector-housing (Fig. 2). The effective measurement point is defined at 1 mm from the top of the detector housing.

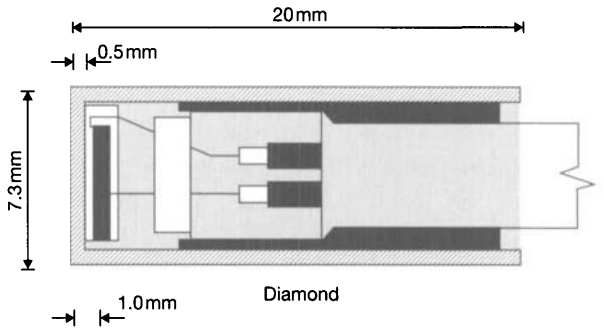

Figure 2. Longitudinal cross section of the diamond detector. The +100 V bias is applied through the gold contacts on the diamond surface.

Diamond detectors work as solid-state ionisation chambers.[52] The absorption of ionising radiation induces a temporary change in the electrical conductivity of the diamond through the production of electrons and positive holes that have sufficient energy to be free to move through the crystal.[52] Its current is linearly proportional to the dose rate.[50,55] Its dose rate dependence is sufficiently low to be neglected.[50] The energy-dependence of the response is determined by the effective atomic number Z = 6, which is close to soft tissue Z = 5.92 – 7.42.[50] The photon energy range is from 80 kV to 20 MV, the electron energy

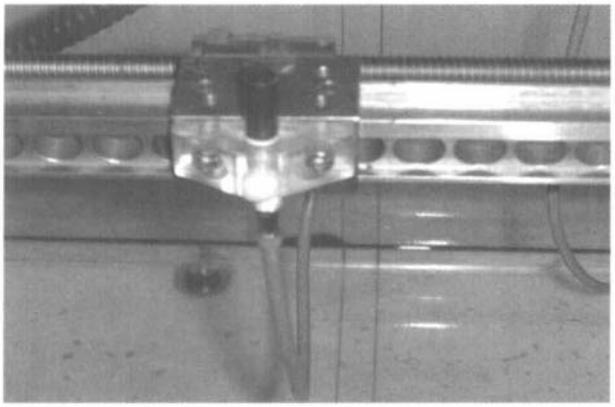

Figure 3. Diamond detector attached to the drive mechanism of the water tank.

range is from 4 to 20 MeV, and the dose rate range is from 0.05 to 30 Gy/minute.[58] An operating bias of +100 V, as recommended by PTW[35,52,55,58] is applied through 0.05–0.6 μm gold contacts and 50 μm silvered copper wire. It has a flat top-surface and a small size – the naturally grown diamond is sealed in a cylindrical polystyrene housing of diameter 7.3 mm (Figs 2 and 3).[35,58] It can be connected to the dual channel electrometer of the PTW-MP3 Therapy Beam Analyser. The diamond detector is therefore an excellent choice as a detector by virtue of its sensitivity, geometry and high spatial resolution.[50] A disadvantage of a diamond detector is its high cost.

CONCLUSION

The advantages and disadvantages of various detectors for measuring surface and build-up dose in radiotherapy have been described. The extrapolation chamber is the instrument of choice. Parallel-plate ionisation chambers, TLDs, diodes and photographic film are used frequently. The diamond detector is also a suitable and convenient instrument for surface and build-up dosimetry in radiotherapy.

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