Recent advances in non gel tissue equivalent dosimeters

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1. Introduction

This review highlights some of the developments in radiation dosimetry, other than gel dosimetry, that are relevant to radiotherapy and have been reported since the previous DOSGEL meeting in 2006. The results included in this presentation were obtained primarily from searches of the PubMed database.

Two advantages of gel dosimetry are the tissue or water equivalence of the dose response and the inherent 3D geometry of the gel phantoms. However, in practice ionization chambers and film have been the most common dosimeters for clinical radiation dosimetry. Ionization chambers are easy to use and provide precise measurements. Protocols have been developed so that uniform results can be attained throughout the world. Silver halide film provides excellent spatial resolution and with careful processing can provide reproducible results. However, ionization chambers are limited by spatial resolution and detector perturbations of local dose gradients. Silver halide film’s major drawback is the difference in energy response relative to water or tissue which becomes measurable in regions of high dose gradients and where energies less than 200 keV are present. As the complexity of delivered radiotherapy treatments increases verification at many distinct points becomes essential because many smaller fields are used to deposit the dose. This leads to a situation where dose delivered from the beam penumbral regions is a significant fraction of the total dose. Accurate measurements in penumbral regions, where the dose gradient is high and the energy spectrum is rapidly changing require small tissue or water equivalent dosimeters to avoid dose inaccuracies. If the beam is incorporated into a treatment planning system then errors would be propagated in subsequent calculations.

In this review highlights of advances for point (0D) and planar (2D) dosimeters are presented. Dosimeters that are near water or tissue equivalent are more relevant for direct comparisons with 3D radiation sensitive gels and plastics. This equivalence and sufficient dose sensitivities for accurate measurements in the clinically relevant range of 0.01 to 20 Gy range were the criteria for selecting material. Many of the papers are related to small field dosimetry where much of the dose is deposited in high gradient penumbral regions. Often the minor differences in dosimetry measurements in large fields can be clearly observed in the high gradient regions. Conversely, dosimeter systems that are accurate for small field dosimetry should also be the most accurate for larger fields. In the case of 3D dosimetry, the case of small fields with high gradients is also a reasonable place to compare the performance of different dosimetry systems. For example which items result in more accurate dosimetry: scattering versus transparent materials, low diffusion versus no diffusion materials, optical CT versus MRI scanners, laser versus light emitting diode optical CT scanners? It is interesting to
recognize that most of the issues related to film and film densitometers are the same items that require evaluation for accurate 3D optical CT scanning.

2. Point detectors

Intensity modulated radiotherapy (IMRT) is becoming standard practice because multi-leaf collimators and IMRT capable planning programs are now standard technologies for new equipment purchases. Key to IMRT commissioning is accurate dosimetry for small radiation fields or beamlets. Small, water equivalent dosimeters are ideal for these measurements. Some of the examples listed could also be configured for linear, planar or volume dosimetry. For example a crystalline material could be distributed in a line, sheet or fill a container.

2.1 Ion chambers

Ion chambers are the local standard dosimeter in nearly all radiotherapy centers. They are calibrated against a national standard. Ion chambers give precise measurements and their accuracy is tied to the dosimetry protocol employed. The accuracy of relative dosimeters is directly tied to the accuracy of the ion chamber calculated dose.

Wang and Rogers have compared Monte Carlo calculations of replacement factors, $P_{\text{repl}}$ (or $p(\text{cav}) \cdot P(\text{dis})$ in IAEA notation), with recent measurements and found closer agreement than with values recommended in current protocols [1]. The magnitude of the discrepancies can be up to 0.5%. They recommend updating the parameters in current protocols to reflect these more accurate values, which reduce variations between measurement and calculations. As the differences between ion chamber and other dosimeter systems approach the 2% level the question becomes which measurement is more accurate.

Farmer type axial chambers and parallel plate chambers perturb the dose distribution that would be deposited if the chamber is replaced with water or tissue equivalent material. For this reason, smaller chambers such as the Pin-Point micro-ionization chamber were developed. While providing higher spatial resolution and few perturbations these smaller chambers also have lower sensitivity. Recently, to provide better agreement with higher performance detectors such as diamond detectors the PTW chamber was modified to an aluminum electrode (type PTW 31014). Profiles for MV photon beams measured with the Pin-Point chamber were 0.6 mm larger than those recorded with EDR2 film [2]. Stem and polarity effects up to 0.5% were measured for larger fields, requiring corrections to obtain accurate measurements.

2.2 Solids (powders, crystals)

In general, powders and crystalline materials can act as dosimeters by generating metastable species such as molecular radicals and populating excitation traps. If these materials are primarily organic then dose response will be essentially water or tissue equivalent. Quantitative detection can involve microwave photon absorption with electron paramagnetic resonance spectrometers or luminescence stimulated thermally, optically or chemically. Alanine / EPR dosimetry is one of the most thoroughly investigated powder dosimeters, but its dose sensitivity is low for the 0.01 to 20 Gy range. However, comparisons with XV film, mini-TLD and ionization chamber demonstrated agreement with 1 mm diameter by 3 mm long paraffin-alanine rods [3].

Lithium formate monohydrate with EPR dosimetry has been investigated due to increased sensitivity compared to alanine [4]. Dose response in the 0.5 to 3.5 Gy range was reported and a thorough uncertainty analysis determined a 2.5% uncertainty for doses greater than 3 Gy. The work suggested further increases in sensitivity may be achieved from similar materials.

2.3 Optically stimulated luminescence (OSL)

Carbon doped aluminum oxide ($\text{Al}_2\text{O}_3:\text{C}$) bound to a polystyrene sheet forms a 2D OSL film dosimeter. Following irradiation the recorded dose is read by recording the blue luminescence stimulated by the absorption green light. Upconversion is a very sensitive optical readout mechanism.
since photomultiplier tube phosphors that are much more sensitive to blue light are available. This OSL material is now commercially available from Landauer Inc. in the form of 2 mm diameter dots (Nanodot dosimeter) or 15 cm strips. The dots can be read with an OSL reader (Microstar, Landauer) or returned to the manufacturer for batch readings. The performance of the commercial dosimeters and readers revealed ~2% variations in response for prescreened detectors at doses > 0.1 Gy and a dose uncertainty of 2% (at 2σ) [5]. No fractionation effects, energy or dose rate dependence was found. A thorough characterization of the earlier commercial dosimeter (InLight/OSL Dot) and the Microstar reader was recently reported [6]. This system has several advantages over conventional thermal luminescence products: it is much smaller, does not require compressed gas, there are no annealing ovens, samples can be read repeatedly to improve precision, samples can be irradiated repeatedly up to a total dose of approximately 20 Gy before a simple optical annealing is required to restore initial dose response and the system is less expensive. Jurisinic reported: repeat reading variations of 0.6%, following a 10 minute fade interval, sensitivity was constant up to 20 Gy, dose response nearly linear to 2 Gy and then becoming supralinear, energy, dose per pulse independence for the typical ranges of a linear medical accelerator. Also, temperature and angular independence simplified usage for in vivo dosimetry. These results indicate that OSL systems will be very practical for quantitative megavoltage dosimetry. A second study evaluated the same product but readings were performed by the manufacturer typically two weeks post irradiation [7]. The deviations in measurements were typically lower for this study possibly due to a larger number of samples and to higher precision in the Landauer commercial reader. The results clearly show a 4% decrease in energy response from 6 MV to 18 MeV. The work also demonstrated the relative dose response of OSL, GafChromic EBT and Kodak X-Omat V films 5 cm outside the beam edge for 6 and 18 MV photon beams. The energy responses indicate an over response relative to water or tissue for the low energy components of the scattered photons. Linear response was up to 2 Gy was also reported in this study. Authors noted that OSL film may be useful for 2D dosimetry once appropriate readers are developed.

3. Two dimensional detectors

The optical density of films is measured with several types of densitometers and these instruments need to be independently calibrated for accurate dosimetry. As clinics evolve into digital imaging, the highly developed automatic film processors for silver halide film are quickly disappearing and new facilities do not include space for this technology. For this reason there has been a dramatic shift towards the usage of radiochromic film that is self developing. Also, a new version of radiochromic film GAFChromic EBT (external beam therapy), was recently introduced that has higher dose sensitivity than previous versions.

3.1 Plastic scintillator sheet

In principle, plastic scintillator sheets can be adapted for two-dimensional water equivalent dosimetry. The characteristics of plastics can be precisely tuned for physical and electronic density providing near ideal agreement with tissue or water dose responses. Plastics are inexpensive, chemically inert and can be formed into arbitrary shapes and volumes. Several approaches have been demonstrated to account for the light not generated by absorbed dose in the scintillator detector. While most of the research has concentrated on fiber based scintillator systems there are a few reports concerning 2D measurements. In the previous review the work of Petric et al was reported. In that study the scintillator plate was sandwiched between water phantoms [8]. A similar geometry has been investigated by Frelin et al with the added variation of replacing the water with polystyrene [9]. The polystyrene introduces substantial increases in phantom Cerenkov, fluorescence, absorption and optical aberrations. Also, a checkerboard plate was included to allow measurement if interference light spatially. Filtering to correct for the effect of this grid array led to measurable artifacts in the processed images. The work clearly shows the added complexity of trying to discriminate the
scintillator from phantom signals. The optical problems described in this study are analogous to effects present in broad beam optical CT scanning.

3.2 Radiochromic film
Radiochromic films from International Speciality Products known as GAFChromic films have been widely used as tissue equivalent 2D dosimeters. A comprehensive reference list is provided on the manufacturer’s website, www.ispcorp.com. EBT is the most sensitive film to date and is suitable for measurements in the 0.1 to 8 Gy range. The film contains two active layers for a total thickness of 0.229 mm and 0.3 % Li and 0.3% Cl appear to be the key sensitizing additives. Cheung et al have also investigated the post-irradiation darkening of EBT film and recommended that quantitative measurements include a wait time of at least 6 hours [10]. Otherwise a calibration film with the same post-irradiation time should be referenced.

The higher sensitivity radiochromic films have also have higher energy absorption spectra and film scanners optimized for the older films will be of limited value in reading the newer film types. Laser densitometers at 633 nm are well matched to the main absorption peak. Soares has published a comparison of the common radiochromic films measured with several densitometers [11]. The film uniformity was measured to be 6% peak to peak and highlight the importance of film orientation for scanning to minimize polarization effects. Calculations of mass-energy absorption coefficients relative to water predict an over response at energies less than 100 keV. The absorption spectrum as a function of dose was evaluated in detail and implications for quantitative dosimetry clearly addressed by Devic et al [12]. The spectrum was decomposed into 8 peaks and the dose response of each peak was presented. The authors recommend that 20 nm bandwith light sources centred at 583 and 635 nm would be efficient for effective densitometry. The red band would provide higher sensitivity at low doses and the yellow band would be useful for higher doses. This paper discusses many issues that are also relevant to the design of optical CT scanners. It would be useful for clinical physicists if the same scanner could be optimized for both EBT films and the 3D radiochromic plastics and gels. Possibly more radiochromic 3D materials will be designed to have spectra with peaks at similar wavelengths to EBT film. Film orientation was also examined by Butson et al and they found up to a 15% variation in response at 50 cGy with film orientation [13]. This value decreased to 4% at 3 Gy but was a 3 fold larger affect that for previous versions of GAFChromic film.

Flatbed document scanners have been widely evaluated for quantitative 2D film densitometry based on the high spatial resolution achievable with a very low cost commercial product. However, these devices are generally not well matched to the spectrum of EBT film and scatter introduces significant artifacts. Because of these limitations users should be cautious when using such devices for quantitative dosimetry. Many groups have reported corrections to improve the performance of these devices but scanners optimized for EBT film will need to be developed before the full potential of this film is realized. Very effective corrections can be obtained by scanning films previously irradiated to known steps in dose [14,15]. Because EBT film is nearly independent of energy the dose calibration curves generated at one field size are valid for other field sizes, unlike silver based Kodak X-Omat V film [16]. This simplifies calibration procedures. Another advantage of an energy independent film is that measured beam penumbras are smaller and more accurate than for silver films [17]. The measured 80%-20% penumbra for a 6 MV, 10 cm x 10 cm field with EBT film was 0.2 mm and 0.6 mm smaller relative to EDR2 and XV films respectively. These differences can introduce measurable errors when modeling penumbras in treatment planning systems for IMRT calculations. Further documentation of the performance of EBT film with the Epson 1680 scanner reported a 1.3% standard deviation at 2.3 Gy in water by using at least two independent film measurements in the center of the scanner [18]. A study of dose rate, depth, field size, fractionation and electron beam energy demonstrated that a single energy, single depth and single cone size is sufficient for electron beam dose response calibration to an accuracy of +/- 4% [19]. Higher accuracy requires individual beam energy calibrations.
Attempts at adding coloured and polarized filters to commercial flatbed scanners has provided additional data suggesting that customized scanners for EBT film are required to realize optimum dosimetry [20]. The limitations of flatbed scanners for quantitative measurements were further documented by demonstrating variations in response along the CCD array and large film orientation effects and heating of film during repeated scans [21,22]. An early design of an LED based scanning spot densitometer optimized for EBT film has demonstrated sub millimeter spatial resolution, with no scatter or interference or rotation artifacts [23]. More expensive film scanners, designed for digitization of colour film slides have been evaluated and are promising if the red and green LED sources can be changed to match the EBT film absorption peaks [24]. Possibly these instruments could also be modified for high resolution optical CT scanning of smaller objects within the available 9 cm x 6 cm aperture.

The high spatial resolution of film allows certain dosimetry measurements to be easily performed. For example, accurate skin dose measurements at a 70 micron depth have been demonstrated with EBT film [25]. X-ray beams with energies less than 1 MV are under investigation for specialized treatments that require small penumbras such as stereotactic radiosurgery of small intracranial lesions and for radiotherapy of small animals. EBT film with digital microscope readout had been demonstrated as an effective method to measure penumbras to within 30 microns [26]. Finally, EBT film with an Epson 1680 scanner has been verified as a clinically acceptable replacement of radiographic film for QA of stereotactic radiotherapy procedures [27].

4. Accurate 3D positioning phantoms

EBT film has another practical advantage in being insensitive to immersion in water because of the laminated construction. Silver based films must be protected from high humidity and emulsions cannot be wetted. Often air pockets get trapped in light and water tight custom film jackets and lead to dosimetry artifacts. Water phantoms are versatile for performing 3D dosimetry since dosimeters can be placed at the optimum locations within the phantom. Pallota et al developed a water phantom suitable for arc therapy and IMRT and demonstrated usage of EBT and laminated EDR2 film [28]. Gels could easily be inserted into this phantom as well.

Finally, motion tracking during treatment delivery continues to be developed for routine radiotherapy. One approach to QA dosimetry is to have 3D motion control for the dosimetry phantom. A three stage linear motion movable phantom has been developed and characterized [29]. The moveable stages have 100 mm of motion and 0.1 mm accuracy with a maximum error in absolute position of 0.56 mm. Such accuracy will be necessary for high resolution 3D dosimetry when motion is involved.

5. Summary

In the last two years OSL dosimetry and EBT film have been introduced into clinical usage. The commercial OSL system from Landauer is much simpler to implement than thermal luminescence dosimetry systems. The performance is sufficient for quantitative MV dosimetry. EBT film has quickly become established in clinics using flatbed document scanners for readout. The true performance of this film requires scanners and densitometers that optimize the light sources to the main peaks at 583 and 639 nm and minimize the artifacts related to interference, scatter and film orientation. Possibly a single scanner will be developed to perform both EBT film dosimetry and optical CT scanning and more 3D radiation sensitive materials will be developed that can be probed at these same wavelengths.
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