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Review of the dose-to-water energy dependence of alanine and lithium formate EPR dosimeters and LiF TL-dosimeters – Comparison with Monte Carlo simulations

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ABSTRACT

The dose-to-water energy dependence may be defined as the dosimeter reading per absorbed dose to water for a given radiation beam relative to that for ^{60}Co γ rays. The purpose of this work was to review the literature on the dose-to-water energy dependence of lithium formate and alanine EPR dosimeters and LiF:Mg,Ti TL-dosimeters for clinical beam qualities and to compare the findings with Monte Carlo simulations.

Monte Carlo simulations of the energy dependence of lithium formate and alanine EPR dosimeters and LiF:Mg,Ti TL-dosimeters were performed using the EGSnrc code. The following common clinical radiation qualities were applied: 4–24 MV photons, 4–20 MeV electrons, 50–200 kV$_p$ X-rays, ^{192}Ir γ rays, and ^{60}Co γ rays as the reference.

All dosimeter materials showed measured and Monte Carlo simulated energy responses around unity for MV photons, electrons and ^{192}Ir γ rays, except LiF TL-dosimeters which showed an average under-response of approximately 3% for electrons. For medium energy X-rays (50–200 kV$_p$), LiF displayed an increasing overresponse with decreasing energy to a maximum of about 40% for 50 kV$_p$ X-rays. The two EPR dosimeter materials showed decreasing energy response with decreasing X-ray energy, but lithium formate was less dependent on energy than alanine. Comparisons between Monte Carlo simulations and measurements revealed some deviations for medium energy X-rays, which may be due to LET-effects caused by low energy electrons.

In conclusion, lithium formate is the dosimeter material with the lowest energy dependence over a wide range of clinically relevant radiation qualities, which clearly is advantageous for accurate dosimetry.

1. Introduction

Common dosimeters for use in radiotherapy are ionization chambers, semiconductor diodes, radiographic and radiochromic films, thermoluminescence (TL) dosimeters and diamond detectors. On a daily basis, on-line (active) systems like ionization chambers and semiconductor diodes are most convenient, but there are situations where good off-line (passive) dosimetry systems are needed. For instance, measurements involving cables may be hard or impossible. Also, there are situations where small detectors are required or where on-line systems have limitations (e.g. in beam penumbras or at very shallow depths). Suitable off-line dosimetry systems in radiotherapy are, for instance, films, TL dosimeters, gels and electron paramagnetic resonance (EPR) dosimeters.

The use of L-α-alanine (alanine) EPR dosimeters in radiotherapy has a 30 year long history (Regulla, 2000; Regulla and Deffner, 1982), and is recognized as an accurate standard dosimetry method (Anton, 2005; Hayes et al., 2000; Mehta and Girzikowsky, 1996). Alanine has a stable radiation-induced signal and the readout is perfectly non-destructive. In comparison, the signal of TL dosimeters at radiotherapy dose levels is reset when being read (Kron, 1994, 1995). Alanine and the most common TL dosimeter material, LiF:Mg,Ti, both have compositions close to water, but alanine is less sensitive. Furthermore, the dosimeter signal from irradiated alanine is linear with absorbed dose from about 1 Gy (FWT, 2010), while LiF:Mg,Ti shows a supralinear response at doses around and above 1 Gy (Kron, 1994, 1995). Both alanine and

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LiF:Mg,Ti are reported to have low energy dependence over a wide range of radiation qualities (Anton et al., 2008; Bergstrand et al., 2003, 2005; Mobit et al., 1996a, b, 1998; Zeng et al., 2004, 2005).

Efforts to develop a more sensitive EPR dosimeter material than alanine, especially for applications in radiotherapy, have led to the introduction of lithium formate (Lund et al., 2002; Vestad et al., 2003). This dosimeter material has beneficial properties, being 5–6 times more sensitive than alanine, having an atomic composition closer to water than alanine and lithium fluoride (see Table 1) and showing equal or less energy dependence than alanine (Malinen et al., 2007; Vestad et al., 2004; Waldeland et al., 2010a). In addition, the peak-to-peak line width of irradiated lithium formate has been suggested as an indicator of the linear energy transfer (LET) of ion beams (Malinen et al., 2006; Waldeland et al., 2010b). Lithium formate EPR dosimetry has also been demonstrated for clinical dosimetry of different radiotherapy techniques, like intensity modulated radiotherapy (IMRT), brachytherapy and stereotactic radiosurgery (Antonovic et al., 2009; Gustafsson et al., 2008; Waldeland et al., 2010c). A summary of some properties of lithium formate, alanine and lithium fluoride dosimeters is given in Table 1.

In radiotherapy, water is recommended as the reference medium for measurements of absorbed dose for both photon and electron beams (IAEA, 2001). The dose-to-water energy dependence of a dosimeter may be defined as the dependence of the dosimeter reading per unit absorbed dose to water on incident particle or photon energy relative to that for a reference radiation quality (usually ^{60}Co or ^{137}Cs γ rays) (Attix, 1986). A high energy dependence means that large correction factors must be applied if the dosimetry is based on absolute calibration at the reference beam quality. The behaviour of the currently studied dosimeter materials for different clinical beam qualities has been studied by many authors (Malinen et al., 2007; Mobit, 2002; Mobit et al., 1996a, b; Robar et al., 1996; Zeng et al., 2004, 2005), and some deviations between calculations (either analytical or by Monte Carlo) and measurements for low energy X-rays are reported (Adolfsson et al., 2010; Nunn et al., 2008; Olko, 2002; Olko et al., 2002; Waldeland et al., 2010a; Zeng and McCaffrey, 2005). The purpose of the current work was to summarize these reports for alanine, lithium formate EPR dosimeters and LiF TL-dosimeters, and to perform Monte Carlo simulations for comparison.

2. Materials and methods

2.1. Energy dependence and quality correction factors

A dosimeter is irradiated at a depth in water where the absolute dose to water, D_w, is known for a given beam quality Q, resulting in a dosimeter reading, r_Q. The irradiation and measurement is repeated for a reference beam quality Q_0 (typically ^{60}Co γ rays). The measured dose-to-water energy dependence of a dosimeter may be formulated as:

$$F_{Q,Q_0} = \frac{(r/D_\mathrm{w})_Q}{(r/D_\mathrm{w})_{Q_0}} = \frac{(r/D_\mathrm{dos})_Q}{(r/D_\mathrm{dos})_{Q_0}}\frac{(D_\mathrm{dos}/D_\mathrm{w})_Q}{(D_\mathrm{dos}/D_\mathrm{w})_{Q_0}} = G_{Q,Q_0}H_{Q,Q_0}. \tag{1}$$

where $(r/D_\mathrm{w})_Q$ is the dosimeter reading per dose to water at beam quality, Q, $(r/D_\mathrm{dos})_Q$ is the corresponding reading per dose to the dosimeter and $(D_\mathrm{dos}/D_\mathrm{w})_Q$ the ratio between the dose to the dosimeter and the dose to water. The dose to the dosimeter may not be obtained directly from the measurements, but may be estimated by Monte Carlo simulations or semi-analytical methods (e.g. cavity theory). $G_{Q,Q_0} = ((r/D_\mathrm{dos})_Q/(r/D_\mathrm{dos})_{Q_0})$ is a measure of radiation yield in the detector exposed to a user beam quality, Q, to the same when exposed to the reference beam quality Q_0. This quantity is called the *relative effectiveness* of the dosimeter and may be different from unity if the amount of radiation-induced products in the dosimeter (per dose to the dosimeter) differs between Q and Q_0.

$$H_{Q,Q_0} = \frac{(D_\mathrm{dos}/D_\mathrm{w})_Q}{(D_\mathrm{dos}/D_\mathrm{w})_{Q_0}} \tag{2}$$

is the corresponding ratio of absorbed doses, and is calculated by Monte Carlo simulations in the current work. Thus four individual Monte Carlo simulations are needed to calculate this ratio.

In practical dosimetry, one may choose to have a standard dosimeter calibration series at the reference beam quality (point calibration), and correct all dosimeter readings at other beam qualities with a quality correction factor. If the formalism outlined above is followed, $(r/D_\mathrm{w})_{Q_0}$ is the inverse calibration coefficient obtained at the reference beam quality. Following a single measurement at a user beam quality, resulting in a dosimeter reading, r_Q, the dose to water may thus be determined by:

$$D_{\mathrm{w},Q} = \frac{r_Q}{F_{Q,Q_0}(r/D_\mathrm{w})_{Q_0}} = r_Q N_{D,\mathrm{w},Q_0} k_{Q,Q_0} \tag{3}$$

where $k_{Q,Q_0} = (F_{Q,Q_0})^{-1}$ and $N_{D,\mathrm{w},Q_0} = (r/D_\mathrm{w})^{-1}_{Q_0}$. k_{Q,Q_0} is denoted the energy, or quality, correction coefficient, while N_{D,w,Q_0} is the dosimeter calibration factor. Equation (3) is comparable to the general dose equation given the dosimetry protocol IAEA TRS398 (IAEA, 2001). It is preferable to use the measured $(F_{Q,Q_0})^{-1}$ as the energy correction factor, but $(H_{Q,Q_0})^{-1}$ is sometimes used in the absence of a measured estimate. However, as will become evident, it is stressed that using $(H_{Q,Q_0})^{-1}$ as correction factor in equation (3) may lead to erroneous dose estimates for low- to medium-energy X-rays.

2.2. Dosimeters

2.2.1. Alanine dosimeters

Alanine dosimeters are typically produced from a mixture of polycrystalline L-α-alanine and a binder. Studies performed with different binders or composite materials and different amounts of binder have been reported (Chen et al., 2008, 2010; Desrosiers et al., 2006; Galindo and UrenaNunez, 1997), but normally the most reproducible water equivalence and sensitivity are achieved by adding as little binder as possible. Commercial alanine dosimeters with 4% binder by weight are available and this combination seems to be used extensively. Dosimeters may be made small, compact and easy to handle, and are characterized by low influence of temperature, humidity and dose rate (Desrosiers et al., 2008, 2009; Nagy et al., 2000; Sleptchonok et al., 2000). The range of linear dose

Table 1
Properties of water and the different dosimeter materials used in the current work. Properties for both pure crystals and commercially available or laboratory fabricated dosimeters are given.

Material	Effective atomic number	Density (g/cm^3)
Water	7.51	1.0
Lithium formate monohydrate (crystal)	7.31	1.476[a]
Lithium formate monohydrate (pellet)	7.31	1.31[b]
L-α-Alanine (crystal)	6.78	1.424
Commercial alanine dosimeter[c]	–[d]	1.2[e]
Lithium floride (LiF)	8.27	2.64
TLD-100 (LiF:Mg,Ti)	8.27	2.64

[a] Thomas et al., 1975.
[b] Approximate dosimeter density, may vary with pellet production method.
[c] ES 200-2106 (Gamma Service Produktbestrahlung GmbH, Leipzig, Germany).
[d] 4% Binder material by weight (proprietary material and information not provided by Gamma Service).
[e] Bulk density for alanine dosimeters.