

Photometric calibration of a radiochromic gel dosimeter

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Abstract. Measurement traceability of dosimetry systems to standards of measurement underpins reliable radiation treatments. A method to determine the product of the molar linear absorption coefficient and the radiation chemical yield is presented, which provides a means of photometric calibration of chemical dosimetry systems in order that the absorbed dose be determined directly from photometric measurements.

1. Introduction

Polymer gel dosimeters are manufactured from radiation sensitive chemicals, which upon irradiation polymerize as a function of the absorbed radiation dose [1]. These gel dosimeters which record the radiation dose distribution in three-dimensions (3D) have specific advantages when compared to one-dimensional dosimeters and two-dimensional dosimeters [2, 3]. These 3D dosimeters are radiologically soft-tissue equivalent [4] with properties that may be modified depending on the application. The 3D radiation dose distribution in polymer gel dosimeters may be imaged using magnetic resonance imaging (MRI) [5, 6, 7], optical-computerized tomography (optical-CT) [8, 9], x-ray CT [10-12], ultrasound [13-17] or vibrational spectroscopy [18, 19].

To be meaningful as a dosimetry system, the determination of absorbed dose should be traceable to standards of measurement through an unbroken chain of comparisons from a primary standard to the end user measurement. Calibration of dosimetry systems to standards of measurement underpins reliable radiation treatments [20]. The quantity of interest in radiation therapy is absorbed dose to tissue, usually with reference to the measurement of absorbed dose to water [21].

Gel dosimeters are essentially chemical dosimeters, in which chemical changes are induced by the interaction of ionising radiation in the material. In some gel dosimeters (and the case examined here), this radiation-induced chemical change is accompanied by a change in the optical absorbance, allowing dose to be read photometrically. A general technique for the calibration of photometrically-readable chemical dosimetry systems, including gel dosimeters, is presented. The aim of this is to determine a constant of proportionality that can be used to calculate the absorbed dose to gel directly from photometric measurements.



2. Theory

In any chemical dosimetry system, the number of moles of a particular chemical species changed, destroyed or created, Δn , per unit of energy absorbed, ΔE , is the radiation chemical yield, G :

$$G = \frac{\Delta n}{\Delta E} \quad (1)$$

In a given material of density ρ , the G value may be expressed in terms of the change in the concentration of the analyte of interest, Δc , and a proportional change in the absorbed dose, ΔD :

$$G = \frac{\Delta c}{\Delta D \rho} \quad (2)$$

One technique to determine the concentration is photometric measurement of the change in optical density, or absorbance, ΔA , defined by the Beer-Lambert Law:

$$\Delta A = \varepsilon_m d \Delta c \quad (3)$$

where ε_m is the molar linear absorption coefficient for the molecular species of interest at a given wavelength of monochromatic light and d is the optical pathlength through the sample. Combining equations 2 and 3, absorbed dose to the material, in this case gel, ΔD_g , becomes

$$\Delta D_g = \frac{\Delta A}{\rho d \varepsilon_m G} \quad (4)$$

In practice, ΔD_g is converted from the traceable measurement of absorbed dose to water, ΔD_w ,

$$\Delta D_w = \frac{\Delta A}{\rho d \varepsilon_m G} \left(\frac{\mu_{en}}{\rho} \right)_g^w \quad (5)$$

where $\left(\frac{\mu_{en}}{\rho} \right)_g^w$ is the ratio of the mass-energy absorption coefficients for water and gel, assuming charged particle equilibrium conditions exist.

Many chemical dosimeters have dependencies on either the temperature during measurement, t , or the temperature during irradiation, t' , or both. For this reason, the molar linear absorption coefficient is denoted as $(\varepsilon_m)_t$ and the radiation chemical yield is denoted as $G_{t'}$. In the standard Fricke solution [22], the product $(\varepsilon_m)_t G_{t'}$ was recommended [23] to be used rather than individually determined $(\varepsilon_m)_t$ and $G_{t'}$ values, due to a correlation in their respective uncertainties. Grouping these quantities as though they were one quantity avoids the difficulty in considering correlated uncertainties. Grouping of these quantities also helps avoid another complication - in some gel dosimeters, there may be multiple species responsible for the radiation-induced change observed in the optical absorbance measurement. Therefore, in such cases, the product $(\varepsilon_m)_t G_{t'}$ is, strictly speaking, an effective value, and is the sum of this product for all species responsible for optical absorption at the measured wavelength:

$$(\varepsilon_m)_t G_{t'} = \sum_i (\varepsilon_m)_{t,i} G_{t',i} \quad (6)$$

A reference measurement temperature, t_r , and a reference irradiation temperature, t'_r , are arbitrarily chosen to define the molar linear absorption coefficient, $(\varepsilon_m)_{t_r}$, and the radiation chemical yield, $G_{t'_r}$,

respectively [24]. At these reference conditions, the product $(\varepsilon_m)_{t_r} G_{t_r}$ may be determined, to which all other values of $(\varepsilon_m)_t G_{t'}$ are compared. Equation 4 may then be expanded to give

$$\Delta D_g = \frac{\Delta A}{\rho d (\varepsilon_m)_{t_r} G_{t_r} [1 + k_1(t - t_r)][1 + k_2(t' - t_r)]} \quad (7)$$

where k_1 is the measurement temperature coefficient and k_2 is the irradiation temperature coefficient. Thus, once the product $(\varepsilon_m)_{t_r} G_{t_r}$ has been evaluated, the absorbed dose to gel may be calculated directly from photometric measurements.

$u_c(y)$ is the combined standard uncertainty in the quantity of interest, y , and is calculated following the Guide to the expression of uncertainty in measurement [25]:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial y}{\partial x_i} \right)^2 u^2(x_i) \quad (8)$$

The partial derivative is referred to as the sensitivity coefficient, also denoted c_i , and is effectively a weighting factor of each independent influence quantity x_i . The relative uncertainty in the influence quantity is then $c_i u(x_i)/y$.

3. Discussion

Measurement of each influence quantity should be traceable to standards of measurement. For the purposes of dosimeter calibration, absorbance readings are usually obtained for gels prepared in 1 cm cuvettes. The repeatability of multiple absorbance readings, expressed as the standard deviation, indicates only the precision in the measurement and does not account for a possible systematic departure in the measured absorbance from the 'true' or traceable measurement of absorbance. Calibration of the spectrophotometer would provide information on the magnitude of this uncertainty.

The traceable measurement of the absorbed dose standard will have an uncertainty that must be included in the combined uncertainty. Reproducibility of the dose response for multiple batches of the same gel formulation accounts for random variability in the gel preparation. If a dose rate or energy dependence exists, the combined uncertainty should be evaluated under the changed conditions.

This approach only considers the dosimetric calibration of the gel as a radiation dosimeter. It does not consider other influences affecting the dosimeter uncertainty related to variations in the scanning of the dose distribution in 3D discussed elsewhere in the literature [26-28].

4. Conclusion

A technique is presented to determine the product $(\varepsilon_m)_{t_r} G_{t_r}$, for any chemical dosimeter, including gel dosimeters, measured photometrically. Calibration of this constant of proportionality allows the absorbed dose [29] to gel to be calculated directly from photometric measurements.

5. References

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