Preliminary Investigation of the Dosimetric Properties of ‘RadGel’

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Abstract. A preliminary investigation into the efficacy of a new 3D dosimetry material, RadGel™, for verification of radiation therapy dose distributions is presented. Small volumes of RadGel™ were found to exhibit a linear, reproducible response to dose. A gradual increase in optical-density (OD) with time was observed, suggesting scanning should be completed within 18 hours to keep a linear correlation of $R^2 > 0.99$. A larger 10 cm diameter volume of RadGel™ was irradiated with a rotationally symmetric “spoke” plan designed to rigorously evaluate scanner/dosimeter combined performance. The dosimeter was imaged with the Duke Mid-sized Optical-CT Scanner (DMOS). Promising OD and corresponding dose maps were obtained. Edge artefacts were observed and are suspected to be exacerbated by the particular container used in this early study. Further studies will evaluate new containers and methods for refractive matching at the gel-container-fluid interface.

1. Introduction
The use of gel dosimetry has been the subject of significant interest recently as a result of the necessity for a plausible 3 dimensional dosimetry technique for verification and quality assurance of complex radiation therapy techniques, such as IMRT and radiosurgery. The purpose of the current study is to characterize the basic dosimetric properties of a new formulation of gel, called RadGel™, which is a near tissue equivalent material with a CT number of 30 HU. A characterization of a previous formulation can be found in [1]. The properties investigated in this work include absorption spectrum, optical dose response (sensitivity), temporal stability of optical response, dose-rate effects, reproducibility, water equivalence, and volume effects (i.e. whether large volumes respond in a similar manner to small volumes).

2. Methods
Methods are organized into two sections. Section 2.1 details extensive studies on small volumes of the RadGel™ material in order to efficiently investigate a wide range of basic dosimetric properties. Section 2.2 details experiments on a larger volume of RadGel™, to investigate any volume effect as well as the consistency of behavior between large and small volumes.
2.1. Small Volume Cuvette Studies
A series of standard (1 cm x 1 cm) optical cuvettes filled with RadGel™ were irradiated with 6 MV photons in the same beam geometry, consisting of a 10 cm x 10 cm field with an SSD of 100 cm. The cuvettes were individually placed below a 5 cm slab of solid water with 10 cm of solid water below, for backscatter. The center of the cuvette was at a depth of 5.5 cm in solid water and was surrounded by a tissue equivalent bolus. The optical density of individual cuvettes was measured with a Thermo Scientific Genesys 20 spectrophotometer both before and after irradiation.

The first dosimetric property of interest is the absorption spectrum, in order to determine the wavelength at which the maximum ΔOD is observed after irradiation. The radiation induced ΔOD of a cuvette irradiated to 4 Gy was measured with the spectrophotometer over the wavelengths 500 - 700 nm at intervals of 20 nm, with intervals of 2 nm over the range 600 - 612 nm. This higher resolution data coincided with the peak OD change reported in a previous study of ~600 nm (Guo et al. [2]). The next property, optical-dose-response, was measured using 6 cuvettes irradiated to different doses ranging from 1 - 20 Gy. The optical density of each cuvette was measured prior to irradiation and then immediately after irradiation.

The temporal response of optical density was studied by two separate methods. In the first method, three cuvettes were irradiated to a dose of 8 Gy and the immediate change in optical density measured. One cuvette was then scanned by the spectrophotometer at 15 minute intervals for 12 hours, beginning one hour after irradiation. The second cuvette was stored in the refrigerator and the third cuvette was left at room temperature. The ΔOD of all three was then measured 19 hours after irradiation. In the second method, the optical density of the 6 cuvettes used for the dose response study was re-measured at intervals of 17.5, 41.7 and 113.5 hours after irradiation. These 6 cuvettes were stored in the refrigerator between measurements to minimize any temperature effects on the optical density. The cuvettes were allowed to acclimate to room temperature before each measurement in the spectrophotometer. Dose rate effects were investigated by irradiating separate cuvettes to 8 Gy at dose rates of 100, 300 and 600 Monitor Units per minute.

2.2. Volume effect Study
A larger volume 10 cm dosimeter consisting of a plastic bottle filled with RadGel™ was irradiated with a spoke plan modeled after that used by Sakhalkar et al. [2]. The plan was created in the planning system with the AAA algorithm. The spoke plan geometry, consisting of a total of 9 alternating high dose, medium dose and low dose spokes, provides an excellent test of the radial uniformity of dose response of the dosimeter. The spoke plan was created to extend outside the outer diameter of the dosimeter, in order to separate any penumbra effects from edge effects of the dosimeter and bottle. The high-dose spoke was prescribed 6.5 Gy and the medium and low-dose spokes were prescribed 4.7 Gy (72%) and 2.1 Gy (32%) respectively. The gantry was positioned at an angle of 180° with an SSD of 94.2 cm. The Radgel™ dosimeter was placed in a water bath and the plan was delivered with 6 MV radiation from a Varian 600c. The ΔOD of the Radgel™ dosimeter after irradiation was measured using the Duke Midsized Optical Scanner (DMOS), which is a telecentric optical-CT system. More details of the principle of the DMOS scanner are described in an accompanying abstract by Thomas et. al.[3] and elsewhere [4-6]. A solution of ~7% (by volume) ethylene glycol in water was used for refractive index matching of the dosimeter. The measured ΔOD was then compared to the calculated ECLIPSE dose distribution using profiles and gamma maps.

3. Results and Discussion
3.1. What is the optimal scanning wavelength?
The change in optical density as a function of wavelength for the first cuvette irradiated to 4 Gy is shown in Figure 1(a). The peak of this response curve occurs at a wavelength of 608 nm and has a width of ~100 nm. A wavelength of 608 nm was therefore selected for all further measurements of the optical characterization of RadGel™.
3.2. The Response of Optical Density as a Function of Dose
The immediate OD response of the six cuvettes irradiated with doses ranging from 1 - 20 Gy is displayed in Fig. 1(b). A linear regression of the data is also included resulting in an optical density response of 0.010 (Gy cm)$^{-1}$ with a correlation of $R^2 = 0.997$, showing a remarkably linear response.

![Fig. 1(a) Immediate OD Response](image1.png)

**Fig. 1 (a)** the spectral response of RadGel™ cuvette after irradiation dose of 4 Gy. Maximum response was found at 608 nm. **(b)** The immediate measured change in optical density of the RadGel™ cuvettes after irradiation with 6 MV photons of doses ranging from 1 to 20 Gy.

3.3. Temporal Response of Optical Density
The results of the 12 hour, 15 minute interval study of the temporal response of OD in a single cuvette are shown in Fig. 2(a). A linear OD darkening of the RadGel™ of 0.009 (hour cm)$^{-1}$ was observed. Also included in this plot are three data points showing the OD response of cuvettes stored at different temperatures 19 hours after irradiation. A clear increase in OD change is observed with increasing temperature, suggesting a significant temperature dependence of the temporal response. The results of the temporal response of OD with dose for the 6 cuvettes irradiated to differing doses are shown in Fig. 2(b). There are two interesting effects to notice. The first is that the rate of darkening is significantly higher for higher dose points and the second is that the linearity of response is breaking down over time.

![Fig. 2(a) Temporal OD Response](image2.png)

**Fig. 2 (a)** The change in OD of a representative RadGel™ cuvette irradiated to 8Gy. Also included are the values 19 hours after irradiation for 3 cuvettes (cross marks) stored at different temperatures. **(b)** The measured change in OD of the 6 RadGel™ cuvettes after irradiation to different doses determined at 17.5 hours (blue), 41.7 hours (red) and 113.5 hours (green) after irradiation.
3.4. Dose Rate Response and Reproducibility
The ΔOD after irradiation of RadGel™ cuvettes was found to be extremely reproducible with no effects attributable to the delivered dose rate. The immediate ΔOD’s were unaffected by dose rates of 85 - 500 cGy/minute. Dose rate effects below this range are expected to be indistinguishable from the temporal effects discussed previously.

4. Large Volume Studies
A qualitative comparison of a central slice of the calculated and measured spoke plan dose distribution is shown in figure 3. The alternating intensities of the spokes are clearly visible in both distributions.

The edge of the dosimeter is very bright suggesting a difference in index of refraction of the plastic bottle and the RadGel™ inside the bottle. This leads to significant edge effects which should be remedied by selection of an appropriate container for the RadGel™.

Fig. 3 (a) Calculated dose distribution in the central axial slice of the Spoke irradiation delivered to the 10 cm diameter RadGel™ dosimeter. (b) Reconstructed Optical-CT image of the change in OD in the same slice.

Figure 4 (a) shows the gamma map (8% difference, 3mm DTA) calculated for the difference of the images from Figure 3. As expected, the outer edge of the dosimeter is in poor agreement with the Eclipse calculations due to pronounced edge artifacts arising from the difficulty in matching refractive-indices at the fluid/plastic/RadGel™ interface. However, a reasonable pass rate of 83% is found for the inner 3.5 cm radius of the dosimeter. If the gamma criteria are relaxed to a 10% difference, the pass rate increases to 87% for the inner 3.5 cm radius. Figure 4 (b) shows a CT scan of the dosimeter placed in a water bath. The line profile shows the CT number of RadGel™ to be ~ 30 HU, consistent with the surrounding water. The spikes in CT number correspond to the walls of the plastic container.
Fig. 4 (a) Gamma map calculated for the 8% difference, 3mm distance to agreement between the Optical-CT measurement and the Eclipse calculation shown in Fig. 2. A pass rate of 83% is found for the inner 3.5 cm radius of this dosimeter. (b) CT scan of plastic container filled with Radgel\textsuperscript{TM} immersed in water.

5. Conclusions

This preliminary investigation of the dosimetric properties of Radgel\textsuperscript{TM} has produced promising results. The linearity of response found in the cuvette studies and the reproducibility of response are attractive features. The temperature dependence of the temporal response suggests that storing the Radgel\textsuperscript{TM} in a refrigerator after irradiation will significantly slow the OD darkening and allow for an 18 hour period in which the dose response remains linear. The results of the large volume study produced good images of the OD changes in the dosimeter. Strong edge artifacts were observed, however, which are attributed partly to a degree of light scattering in the container walls, and partly to the challenge of achieving a good refractive match at the gel-plastic-fluid interfaces. Further work is anticipated to provide improvements in these areas.

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