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Making and assessing 3D dosimeters

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Abstract. Several 3D dosimeters are commercially available. However, there are many circumstances that require a customized 3D dosimeter. Examples include feasibility tests of non-standard treatment modalities, inhomogeneous tissue configurations, unique shapes and sizes and teaching. In this session, general approaches for preparing radiochromic dosimeters, Fricke and polymer gel dosimeters, micelle gel and silicone dosimeters were presented. Advice will be given to developers of new 3D dosimeters. For optical readout, light absorption and scatter can limit the practical size of dosimeters. Specifically, increasing from 5 to 15 cm diameter dosimeters is optically challenging. Strategies to maximize initial optical transmission were presented. For MRI readout, the dose resolution is determined by both the dosimeter sensitivity and the pulse sequence parameters and the accuracy is determined by the sensitivity of the dosimeter to temperature and dose rate, next to imaging performance. For X-ray CT imaging, the dose resolution is determined by the sensitivity of the dosimeter which largely depends on the polymer density that can be achieved. The importance of characterizing the dosimeter in terms of dose sensitivity and stability, spatial integrity, dose rate and fractionation dependence, oxygen and ambient light sensitivity, temperature sensitivity and thermal history were emphasized. The dosimeter requirements also dictate the types of vessels and scanners appropriate for readout. For example, the preferred dosimeter formulation may include a compound that is incompatible with the preferred vessel.

1. Introduction

This report summarizes a gel dosimeter preparation presentation from the IC3DDose conference in Kunshan, China. Strategies for obtaining useful 3D dose data, were emphasized with reminders to read the literature, especially the previous proceedings. The audience was also reminded to assess commercially available products, before investing in gel preparation. Examples that may not be suited to commercial products include feasibility tests of non-standard treatment modalities [1-7], inhomogeneous tissue configurations [8-12], unique shapes and sizes [13-17] and teaching [18]. Likely, commercial suppliers are willing to place their materials in custom vessels supplied by the users, if they are chemically compatible. General approaches for preparing radiochromic dosimeters [19-21], Fricke [22, 23] and polymer gel [24-27] dosimeters, micelle gel [28, 29] and silicone dosimeters [30-32] were presented. Two applications were used to demonstrate some issues to consider. The first dosimetry example included: optical CT readout of a 15 cm diameter, cylindrical, non-diffusing, radiochromic hydrogel containing small fields with 20 Gy maximum dose. And the second example was: normoxic polymerization gels with MRI or x-ray CT readout. Small field depth doses and profiles are challenging dose distributions but simple to compare against commissioning data and many of the presentations at the conference used small fields to assess their 3D dosimeter performance.



The application, dosimeter material, vessel and readout technology are interdependent, see figure 1. For example, oxygen impermeable, plastic vessels are required for most water-equivalent, dosimetry measurements. These vessels should also be transparent, thin and of uniform thickness for optical CT readout. In other cases, the gel material may contain alcohols or chlorinated solvents which restrict compatible plastics. While there are many published studies on 3D gel dosimeters, users were reminded they must critically assess their samples, whether purchased or made in laboratory, for accurate measurements of 3D dose distributions.

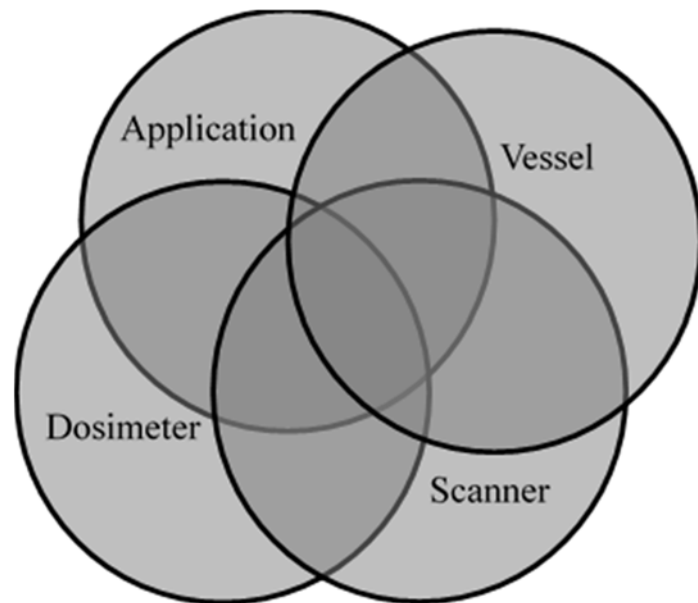


Figure 1. Diagram showing interdependence of factors to consider for 3D dosimetry measurements.

2. Presentation

Many of the key points were made by both authors. These include: minimize thermal and chemical gradients, prepare gels at lowest practical temperatures, minimize exposure to light at photosensitive wavelengths.

2.1 Vessels

Laboratory glassware is generally used for gel preparations because of its chemical inertness and low oxygen permeability. Dosimeter vessels are generally plastic with polyethylene terephthalate (PET) the most common material due to low oxygen transport, low scatter and good optical quality. Barex has been used for anoxic polymerization gels because of its exceptionally low oxygen permeability (figure 2).



Figure 2. Antropomorphic shaped Barex phantom (a) and glass phantom (b) filled with polymer gel.

Effectiveness of methods to seal vessels must be verified. This is generally performed by measuring spatial uniformity of sample's dose sensitivity. A change in sensitivity near the seal generally indicates an oxygen leak or oxygen in the gas phase above the gel. As storage times increase it is likely the oxygen concentration will decrease due to its reactivity with the dosimeter chemicals, producing organic peroxides. When comparing litre sized or larger samples with smaller samples such as 1 cm pathlength polymethylmethacrylate (PMMA) disposable cuvettes, users should be aware that oxygen permeability of PMMA is relatively large leading to well oxygenated cuvette samples and larger volumes with likely lower oxygen concentrations.

2.2 Laboratory equipment

The first polymer gel dosimeters were fabricated in a specialized laboratory that required perfusion of the sol with nitrogen and a glove-box filled with nitrogen to avoid any oxygen infiltrating in the phantom container upon filling (figure 3).

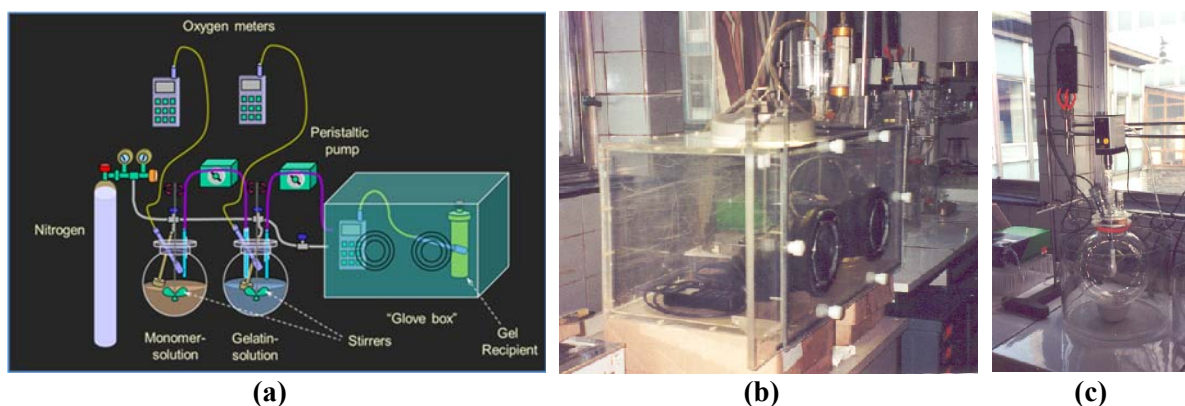


Figure 3. Anoxic polymer gel dosimeters are constructed in an oxygen tight environment, requiring closed vessels, oxygen meters, peristaltic pumps and a glove box (a). Photographs of a laboratory set-up showing a glove box (b) and closed reaction vessels (c).

Oxygen radicals that are formed during radiation can also be captured by use of anti-oxidants which makes the fabrication of polymer gel dosimeters less complicated. However, caution is still required as an excess of oxygen can still inhibit the polymerization reaction [50, 52].

Access to compressed air and vacuum ports is very useful. Compressed air is effective for blow drying vessels to avoid spots and films remaining after evaporation. Blow drying also avoids scratching the plastic surfaces that occurs from mechanical wiping. Vacuum filtration (figure 4) is an effective method to remove debris in both the gelatin solution prior to adding radiation sensitive chemicals and the multiple use, refractive index optimization liquids required for optical CT scanning. Plastic containers are useful for storage and handling of liquids and disposal of gels since several litre volumes are required in the larger scanners. Certain gel formulations can easily be disposed of by chopping the gels into small pieces and leaving to dehydrate and then placing in landfill, for example ferrous xylenol orange or leucocrystal violet gelatin gels. An even better practice is to use redox chemistry or electrochemistry to mineralize the dyes prior to disposal.



Figure 4. Photograph of vacuum filter and flask, filtering refractive index optimization solution of propylene glycol and water.

Temperature control is generally performed with water baths. This approach provides uniform temperatures during preparation, a key factor in obtaining reproducible batches of gel.

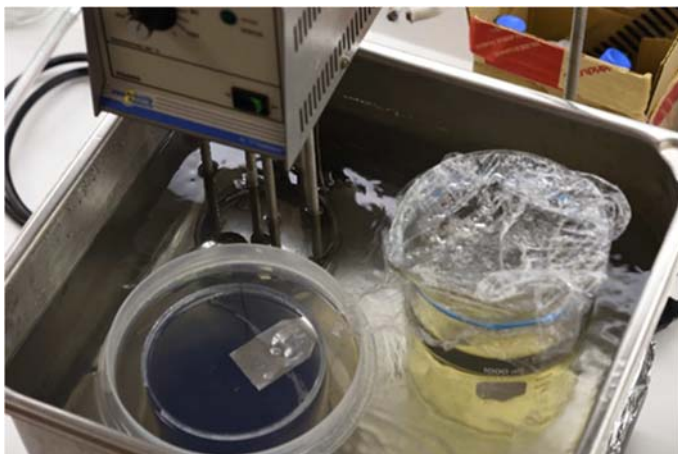


Figure 5. Photograph of water bath with immersion heater, not shown is the magnetic stirrer below the stainless-steel tank.

Figure 5 shows beaker of dissolved gelatin in water and an irradiated blue gel being melted to empty and reuse the vessel.

Generally, gel dosimeters are kept in a fridge around 4 °C to minimize chemical reactions and biological growths to maximize storage time. Shown in figure 6, are three samples of a radiochromic gel prepared with the same concentrations of starting materials but by slightly different steps. Note the differences in scatter and initial colour for the same chemical composition as a caution that preparation details can make a difference. Note also, this particular gel formulation has most uniform response for same day gel samples. For longer times this spatially changing dose response is likely a result of the gelation kinetics of this formulation.



Figure 6. Photograph inside storage refrigerator of three 10 cm diameter gels, same formula but different batches, demonstrating marked changes in initial colour and scatter.

For optical CT readout, the initial background scatter can limit the size of the dosimeter that can be scanned quantitatively. In general, optical CT laser scanners that employ a narrow laser beam have the greatest rejection of stray scattered light and broad beam scanner geometries the least rejection. Colourless dosimeters with transmission >10% relative to water along the diameter should provide quantitative 3D attenuation coefficients with most scanner geometries. For optical readout, light absorption and scatter can limit the practical size of dosimeters [33-35]. For example, a material that is acceptable for a 10 cm diameter sample may be of little value for 15 cm diameter samples. A simple test of scatter is to observe a back-illuminated, transparent ruler, see figure 7.

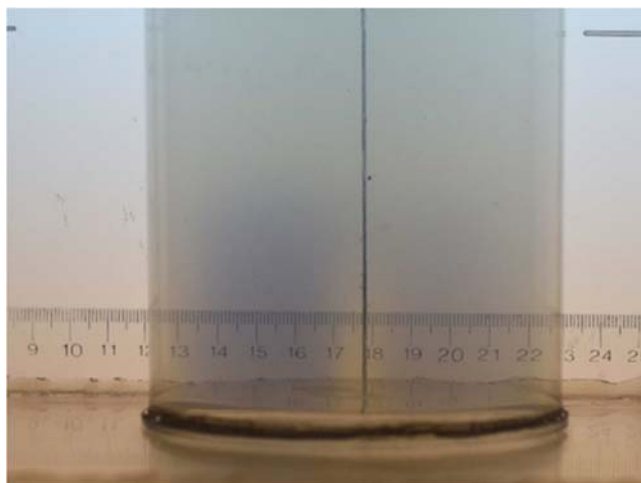


Figure 7. Photograph of back-illuminated transparent plastic ruler viewed through a 10 cm diameter radiochromic hydrogel in a water tank.

In this example, a 10 cm diameter, previously irradiated, gelatin gel is photographed in a tank of water. This image represents a low scatter sample. Note, that near the inside edge of the vessel wall some of the ruler gradations are missing. This is due to the refractive index mismatch between the dosimeter in this custom PET vessel and the surrounding water. A small, fiducial ink dot on the vessel wall can serve a similar purpose when assessing projection images acquired with the system. See dot, beside seam 5 cm above vessel bottom end. Note that most polymer gels exhibit a dose dependent change in refractive index which results in reconstruction artefacts for optical CT scanning.

For MRI readout, the dose resolution [36] is determined by both the dosimeter sensitivity and the pulse sequence parameters [37] and the accuracy is determined by the sensitivity of the dosimeter to temperature [38, 39] and dose rate [40], next to imaging performance.

For X-ray CT imaging, the dose resolution is predominantly determined by the sensitivity of the dosimeter which largely depends on the polymer density that can be achieved [41-43].

2.3 Gel preparation practical tips

Two step by step procedures for a radiochromic and a normoxic polymer gel with gelatin were presented and the cautionary notes were similar. For example, start by sprinkling gelatin onto cold water, to wet before heating to dissolve. After dissolving suspension in 40 to 50 °C water bath with stirring, cool to 30 to 32 °C before adding radiation sensitive chemicals. Remember that oxygen solubility is temperature dependent and that exposure to atmosphere can equilibrate oxygen concentrations before sealing dosimeter vessels. Thermal gradients during gelation, scanning and irradiation can all have measurable effects on 3D response. As the dosimeters increase in size, several hours may be needed to uniformly change the temperature from storage to scanning temperature. For example, a 2.5 litre gel cylinder may require 6 hours to equilibrate from 4 to 20 °C. In order to achieve reproducible initial performance of gelatin dosimeters, the gelatin-water solution can be evaluated for residual oxidizing species by adding ferrous xylenol orange solution to aliquots prior to addition of radiation sensitive chemicals. Specifically, the gelatin solution can be kept warm, for example at 50 °C until oxidizing species have thermally decomposed. This is shown in figure 6 where the solution is sampled until the gel remains yellow orange with the addition of the test FX solution.

2.4 Gel calibration strategies

The importance of characterizing the dosimeter in terms of dose sensitivity and stability [44, 45], spatial integrity [23, 45-47], dose rate [23, 40, 48] and fractionation dependence [49], oxygen and ambient light sensitivity [48, 50], temperature sensitivity [38, 48] and thermal history [51] were emphasized. Sample specific calibrations are generally required. For example, without additional calibration data sets, an individual dosimeter should be irradiated to a uniform dose to first establish spatial dose sensitivity. Assuming, one sample behaves like another may result in spurious results even when samples are from

same batch and have the same thermal history. While each gel formulation has its own features, current experience indicates gelatin gels with lower concentrations of gelatin and same or next day usage provide the most spatially uniform dose response. Other formulations designed for long storage times may have the opposite trend, such that waiting several weeks before irradiation provides more spatially reproducible results. Much effort has been invested in designing calibration strategies, but the user must still verify performance of their specific samples and not assume similarity to published results.

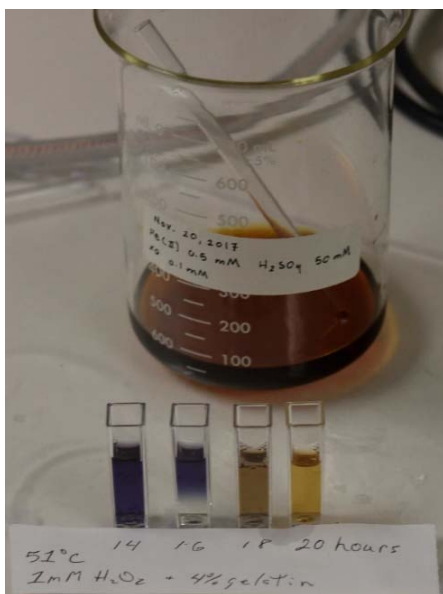


Figure 8. Photograph of colour changes as FX solution added to cuvettes of gelatin-water solution to measure residual hydrogen peroxide.

3. Summary

While gel preparation of several formulations is relatively simple and inexpensive to perform, achieving useful and reproducible results requires methodical development of preparation and calibration procedures. Essentially good lab practice is required to obtain reproducible results.

Disclosure: Authour, K Jordan has a licensing agreement with ModusQA concerning optical CT and radiation dosimetry.

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