Journal of Physics: Conference Series **250** (2010) 012010 doi:10.1088/1742-6596/250/1/012010

The "push-pull" dosimeter: When two pigments are better than one.

Stephen G. Bosi*[1,2], Clive Baldock[2] and Robert Smee[1]

[1]Dept of Radiation Oncology, Prince of Wales Cancer Centre, Randwick NSW 2031 Australia

[2]Institute of Medical Physics, School of Physics, University of Sydney, NSW 2006 Australia

*Corresponding author s.bosi@physics.usyd.edu.au

Abstract. A new kind of gel dosimeter (the "push-pull" dosimeter) is proposed which would contain two spectrally complementary pigments, one which darkens with increasing dose and another which bleaches. The bleaching pigment would be optimised for high sensitivity and the darkening pigment for low sensitivity. By employing dual pigments optimised independently, the usual requisite compromises between sensitivity at low dose and accuracy at high dose would be relaxed. Such a gel, after exposure would be read using two successive optical CT scans employing two different scan wavelengths. The use of dual pigments could also reduce the occurrence of regions of high optical attenuation which generate artefacts in optical CT. This paper also presents results of simulations of the behaviour of such a gel when scanned using optical cone beam CT.

1. Introduction

The choice of dynamic range for any dosimeter involves a compromise between sensitivity and detection limit at the low end, and saturation or loss of accuracy at the high dose end. This compromise is typically resolved by having a range of dosimeters and choosing one with a dynamic range matched to the task. However, in an application such as 3D dosimetry for IMRS/IMRT QA where there is a wide range of dose confined to a small volume, it is challenging to address that compromise.

Moreover, in the case of a 3D gel dosimeter being read optically using either optical cone beam or scanning laser CT, even if saturation of the dosimeter can be avoided, then the highest doses produce regions of high optical density in the gel which can produce shadow and streaking artefacts (Figure 1) and other artefacts such as cupping [1] in reconstructions of the dose map, especially in the presence of noise and stray scattered light.

In this paper, a new design of gel dosimeter is proposed, the "push-pull gel" which relaxes the compromise between accuracy and sensitivity at either end of the dosimeter's dynamic range. This proposed gel would include two separate dosimetric pigments. A mathematical model of such a system has been developed to analyse the optical and dosimetric parameters required for such a pair of pigments. This paper presents some of the initial results yielded by this model.

2. Rationale

The two pigments would be chosen so the maximum dose-induced change in extinction coefficient of the pigments occurs at well-spaced wavelengths, and the wavelength widths of their respective absorption peaks should be narrow enough to minimise spectral overlap. These conditions would allow one to interrogate each pigment separately using a separate optical scan at these two wavelengths, with minimal cross-talk (Figure 2).

One pigment would be optimised to measure the high-dose part of the gel's dynamic range, while the other would be used for low-dose range. Assuming the sensitivity of the two pigments could be independently optimised (for example by varying their concentrations), then the possibility arises that a gel with enhanced dose dynamic range can be produced. The increase in dynamic range by separation of the dynamic range into two separate components, serviced by distinct mechanisms, is reminiscent of the "push-pull" amplifier in electronics, hence the adoption of the name "push-pull" to denote a gel employing two pigments to deal with opposite ends of the dynamic range.

There is another important aspect of this design. One pigment would (as is most typical for dosimeters) darken or *stain* with dose. If however, the second pigment is chosen to *bleach* with dose, then it opens another possibility.

The staining pigment would be optimised for low sensitivity. In that way, it would not saturate in high dose regions. Also, the extinction coefficient in those regions would never be excessive, thus avoiding the optical CT artefacts that result from high attenuation. However, this pigment would necessarily provide poor information in the low-dose regions.

If the bleaching pigment is optimised for maximum sensitivity, then it would serve as the low-dose dosimeter, complementing the function of the staining pigment. The reason for this choice is that in regions of high dose, the bleaching pigment would simply bleach away. In high dose regions, the bleaching pigment would provide no information but also its minimal attenuation would avoid the possibility of high attenuation artefacts.

The possibility that reading a *single pigment* gel dosimeter at multiple wavelengths might improve dynamic range [2] or improve control of image contrast [3] has been suggested before. These suggestions were based on properties of the spectrum of Fricke-xylenol orange gel dosimeter (FXB) which exhibits both bleaching and staining optical wavelength regions. At wavelengths less than ~470 nm, the gel bleaches with dose, while for wavelengths above this, it stains [3]. However, being a single dosimeter pigment, one could not separately optimise both the sensitivity and saturation doses in these two wavelength ranges. The optical extinction coefficients at wavelengths above and below 470 nm in FXB are not independent parameters. Only by using two separately optimisable pigments are the sensitivity and saturation doses at the two ends of the dynamic range truly independently optimisable.

The recent development of a dosimeter based on the radio-bleaching pigment genipin [4] turns this hypothetical design into a distinct possibility.

3. Method

A mathematical model was developed in order to test the underlying optical principles required for the realisation of this new dosimeter and its behaviour in a dual-wavelength optical CT scanner. Both pigments were assumed to be nearly linear in dose in the low-dose range, but to saturate above a certain high dose range.

For each hypothetical pigment, the wavelength of maximum absorption, the width of the absorption peak, the slope and height of the spectrum background, the sensitivity (slope of the attenuation versus dose curve in the linear region), the saturation range and the sharpness of the saturation knee are adjustable. In the current version of the mode, each pigment is assumed to possess a single gaussian absorption peak, although it is easily generalised to include other forms.

Hypothetical dose maps can be input into the model to obtain an extinction coefficient map at the two scan wavelengths which can then be projected numerically to produce simulated optical projections one would obtain in an optical CT scanner. Noise, stray light and other non-ideal

behaviours can also be added. The open-source cone-beam reconstruction software OSCaR2 [5] is then used to reconstruct these projections and the resulting reconstructed extinction coefficient map can then be converted back to dose using the calibration curves and this compared with the original dose map.

For this paper, a dose map (maximum dose 55 Gy) was taken from the dose plan of an actual intensity modulated radiosurgery treatment of the head. The treatment was planned using Radionics XKnife 4. A 2D slice of the treatment plan was then converted into several optical extinction coefficient maps using the model, assuming different sensitivities for the staining pigment. The effect on the reconstructed map, of adding a uniform 10 PPM of stray light to the resulting projections, was examined. The optical scan wavelengths were 455 nm and 617 nm.

4. Results

Figure 3 reveals the reconstructed extinction coefficient map (scanned at 455 nm) resulting from a simulated exposed push-pull gel with a staining gel of moderate sensitivity. Moderate sensitivity can be accommodated because the bleaching pigment (scanned at 617 nm) would be responsible for measuring the lower doses. The two images and accompanying plots in Figure 3 reveal that the addition of 10 PPM of stray light has a negligible effect on the extinction coefficient profile.

Figure 4 shows two profiles taken through extinction coefficient map similar to Figure 3, except that now the sensitivity of the staining pigment is increased by 44%. Without the bleaching pigment, the sensitivity of the staining pigment might need to be increased to improve detection at low dose. Figure 4 reveals the limit to this approach - the increased optical attenuation renders the reconstruction sensitive to stray light.

5. Conclusions

The reduction in sensitivity of the staining dye, allowed for by the presence of the bleaching dye, renders the reconstructed optical attenuation coefficient map (and hence dose map) less sensitive to attenuation-induced artefacts.

Although the push-pull concept was devised for 3D gel dosimetry, a similar principle could also be applied to 2D film dosimeters to increase dynamic range.

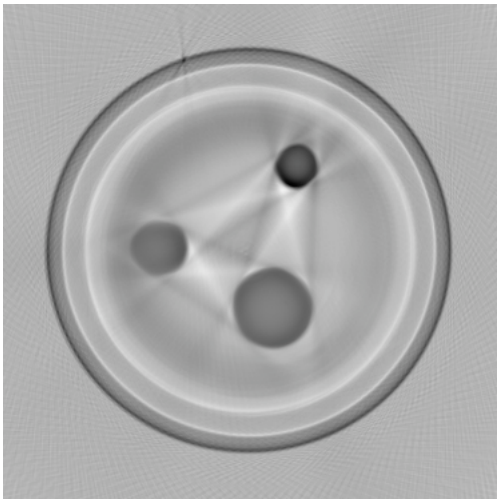

Figure 1. Example of shadow/streaking artefacts in an axial slice of a scanned laser optical CT image of a Dettol gel "finger phantom" with three strongly attenuating fingers. The region surrounding and between the fingers should be uniform grey.

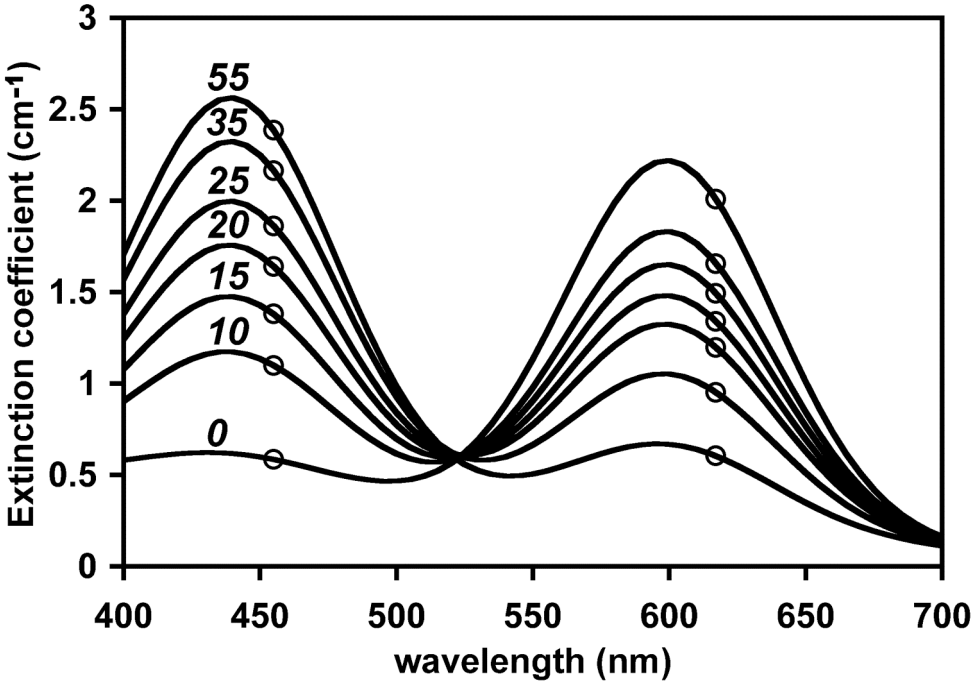

Figure 2. Modelled spectra for a hypothetical gel containing a "push-pull" pair of dosimetric pigments. Each spectrum is labelled by the hypothetical dose in gray. The open circles indicate extinction coefficients measured at two widely-spaced LED wavelengths available for use in the diffuse light source of a Vista optical cone-beam CT scanner (Modus Medical Devices™).

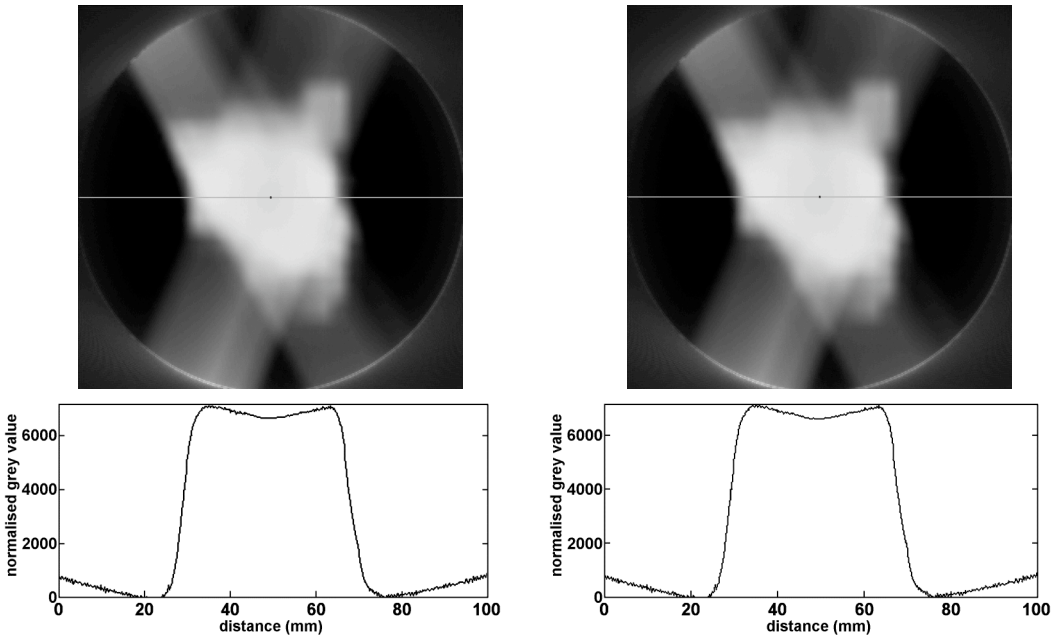

Figure 3. Left: Reconstructed extinction coefficient map (455 nm) for the staining pigment at lower sensitivity, without stray light. Right: Similar reconstruction but with 10 PPM stray light added to optical CT projections. Plots underneath are profiles through the maps, grey values normalised against dosimeter sensitivity. The similarity of the two plots reveals that the effect of stray light is negligible for this dosimeter sensitivity.

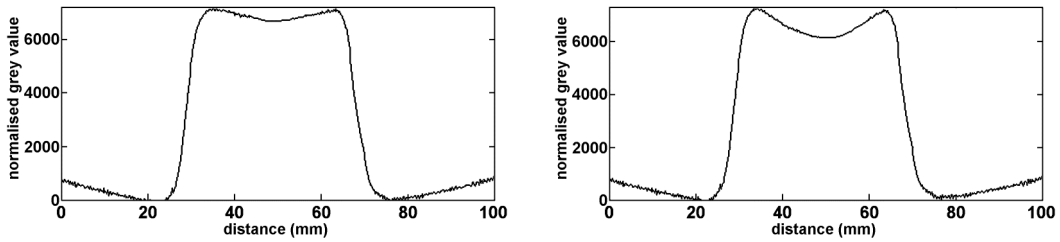

Figure 4. Profiles through reconstructed extinction coefficient maps (455 nm) for a staining pigment 44% more sensitive than in Figure 3. Left: Without stray light. Right: 10 PPM stray light added to optical CT projections. Evident increased cupping in the middle of the bottom profile reveals that even a moderately more sensitive staining pigment renders the gel more seriously affected by stray light.

References

[1] Bosi S.G., Naseri P. and Baldock C. Light scattering-induced artifacts in a complex polymer gel dosimetry phantom. Appl. Opt. **48** 2427-2434 (2009).
Bosi S.G., Naseri P., Puran A., Davies J. and Baldock C. Initial investigation of a novel light-scattering gel phantom for evaluation of optical CT scanners for radiotherapy gel dosimetry. Phys. Med. Biol. **52**, 2893-2903 (2007)

[2] Bero M A, Jenneson P M, Gilboy W B, Glover P M and Doran S J 1999b Faster optical tomography with parallel-beam white light for three-dimensional dosimetry Proc. 1st Int. Workshop on Radiation Therapy Gel Dosimetry July 21-23, 1999, Lexington, Kentucky USA.

[3] Doran S.J., Koerkamp K.K., Bero M.A., Jenneson P., Morton E.J. and Gilboy W.B. A CCD-based optical CT scanner for high-resolution 3D imaging of radiation dose distributions: equipment specifications, optical simulations and preliminary results. Phys. Med. Biol. **46** 3191–3213 (2001).

[4] Jordan K. Optical CT scanning of cross-linked radiochromic gel without cylinder wall. J. Phys: Conf. Series **164** 012029 (2009)

[5] Rezvani N., Aruliah D., Jackson K., Moseley D. and Siewerdsen J., SU-FF-I-16: OSCaR: An Open-Source Cone-Beam CT Reconstruction Tool for Imaging Research. 2007 AAPM Annual Meeting Minneapolis, July 22-26, 2007. Med. Phys. **34**(6), 2341 (2007).
Permalink: http://dx.doi.org/10.1118/1.2760393