Light scattering artefacts in a funnel phantom using optical CT

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Abstract A gelatin phantom containing a funnel-shaped region of high opacity (or optical density OD) was used to examine light-scattering induced artefacts in a cone-beam optical CT scanner used for gel dosimetry. To correctly simulate polymer gel dosimeters, the opacity was introduced by adding a colloidal scatterer to the gelatin. In line profiles of OD taken from 3-D reconstructions of the funnel, those profiles with a long pathlength through high OD regions exhibited a "dishing" artefact, while those of short pathlength exhibited the opposite effect - "doming". These phenomena are accounted for by a model that includes the effect of stray, scattered light.

1. Introduction
Dosimetric polymer gels (such as PAGAT [1]) undergo a change in opacity (measured as optical density) when exposed to radiation due to the formation of cross-linked polymer chains. Optical CT [2,3] can be used to evaluate exposed dosimetric polymer gels. These cross-linked regions result in local microscopic variations in refractive index which act as scattering centres, causing incident light to scatter, resulting in extinction of light from the incident beam. For small to moderate abundances of these polymerised regions, the degree of extinction obeys the Beer-Lambert law:

\[ T = \exp(-x \Delta) \] (1)

where \( T \) is optical transmittance, \( x \) is optical pathlength and \( \Delta \) is optical density (OD or extinction coefficient). OD is proportional to concentration of scattering centres and hence radiation dose over a useful range of dose [3].

Polymer gel dosimeters have the advantage over the radiochromic Fricke gels [4] of being more stable over time. However, unlike (optically absorbing) Fricke gels, the mechanism of extinction in polymer gels is scattering [5] which produces stray light that can result in artefacts in dose distributions deduced from reconstructions of optical CT scans.

In an earlier paper [5], a finger phantom was developed to investigate the effects of scatter on optical density measurements in polymer gels (and hence dose) using optical CT. In the phantom, the commercial antiseptic Dettol™ (Reckitt Benckiser) was added to porcine gelatine to produce "opalescence" or
"Tyndall scattering" typical of a polymerised gel dosimeter. Antiseptic concentration was varied to simulate regions of differing dose.

In that paper, it was found that because of stray light, optical CT would underestimate larger ODs. Also, reconstructions of regions with OD known to be uniform, exhibited a "dishing" or "cupping" artefact; a plot of OD versus position dips lower in the central part of a region compared with its periphery (e.g. Figure 1 right). As dishing can also result from beam hardening, testing this effect in a simulated phantom in which radiation plays no role, allowed the contribution of stray light to this effect to be analysed in isolation.

The severity of both the underestimation of OD and the dishing artefact increases with increasing OD. The aim of the following research was to examine the effects of increasing pathlength and background OD on these two stray light induced artefacts in an optical CT scanner. By developing practical models of the behaviour of stray light in systems like this, it becomes possible to correct for artefacts in dosimeters of this nature but some aspects can also apply to imaging modalities such as X-ray CT which are subject to similar artefacts.

2. Experimental procedure and results

2.1. Scanner
A cone beam optical CT scanner [6] (Vista™ Optical CT Scanner by Modus Medical Devices Inc.) was employed in this study. The scanner (described in detail elsewhere [5]) consists of a diffuse light source illuminating a dosimeter/phantom in a PETE cylindrical screw-top vessel mounted in an aquarium filled with water to match the gel refractive index. A CCD camera takes snapshots of the transmitted projections of the jar which is then rotated incrementally between projections. From these, a 3D map of OD is reconstructed using the Feldkamp back-projection algorithm [7].

2.2. Phantom
Two gels of differing OD were produced by adding differing concentrations of Dettol™ to porcine gelatine. The PETE vessel was filled with the lower OD gel which was allowed to set with a glass funnel centrally mounted in it. Upon removal a funnel-shaped cavity was left, which was then back-filled with the higher OD gel (Figure 1 left). Another PETE vessel was filled entirely with the lower OD gel, to act as a baseline reference (analogous to an unexposed dosimeter) for the scanner. Nominally, the OD within the funnel region of the phantom should be uniform, although it is possible that there is some variation due to uncontrollable inhomogeneities in the rate of setting of the gel. Unlike the finger phantom [5], Dettol™ was also deliberately added to the baseline reference gel to increase the effect of stray light on the process of baseline subtraction.

![Figure 1: Reconstructed slice of the Funnel Phantom and profile plot of OD along the line selection.](image-url)
2.3. Reconstruction

The reconstruction (Figure 1 left) was analysed by generating plots of OD profiles (Figure 1 right) using ImageJ (open source, the National Institute of Health USA).

The gels were designed to have uniform OD within each of the two separate contiguous regions, so any appreciable deviation from uniformity evident in the OD profiles is an artefact. OD profiles were plotted for selections taken through different cross-sections of the funnel, so as to examine the effect of increasing pathlength of the light through the higher OD region. Some examples are plotted in Figure 2. The width of each funnel cross-section (and hence maximum pathlength of light through it) is evident in Figure 2 from the horizontal separation of the shoulders of each plot.

![Figure 2: Profile plots of OD along different cross-sections of the funnel.](image)

As expected and in line with findings for the finger phantom, the wider the cross-section (the longer the pathlength) the more severe the dishing and the more severe the underestimate of OD. However, another effect is evident. For the narrowest cross-sections, the peak exhibits an inverted dishing or "doming". In the finger phantom [5], the cause of the dishing was shown to be stray light entering the scanner camera from in front of the more opaque region, thus underestimating the OD of this region. Dishing occurs because for regions of longest pathlength, the true transmittance is lower, so the stray light represents a larger fraction of the apparent transmittance and so the underestimate of OD through the centre of a region is more severe there. However, explaining doming requires a more complex model than was used to explain the finger phantom results.

2.4. Modelling Data

Modelling was applied to the raw projection images taken by the scanner camera rather than the reconstructed profiles. The light received by the camera was assumed to consist of two components - directly transmitted light (assumed to obey the Beer-Lambert law [Eqn 1]) and stray light, scattering back into the camera indirectly. The intensity of the stray light was assumed to be roughly uniform across contiguous regions of the images in the camera snapshots. This is a simplified but quite a good assumption [5] except in the penumbra region near interfaces. The stray light could either enter the detector directly from scatter within the medium in front of the more opaque region (Figure 3 right), or by reflection off the opaque region itself (Figure 3 left). These two contributions were treated separately in the model. In the model, the baseline reference phantom was treated as a single region, while the funnel phantom was divided into 4 regions: the funnel itself, the background gel on either side of the phantom as seen by the camera, the background gel behind the funnel and the background gel in front of the funnel. The reference phantom and the two background regions were modelled to have two light components:
direct transmittance and a back-scatter component (Figure 3 right). The funnel was assumed to have an extra component - front-face illumination (Figure 3 left).

**Figure 3:** Front-face illumination (left) and backscatter from the intervening medium (right).

Line intensity profiles through the funnel region of the raw projection images were plotted. These were divided by the intensities of line profiles through the baseline reference phantom, to yield an (apparent) transmittance profile plot. The negative logarithm of these plots yielded apparent OD plots. Model apparent OD plots were also generated for each experimental profile and the parameters (true OD and stray light intensity) for each region fitted using a least squares regression. The experimental plots fitted closely, except in the penumbra region near the boundary between background and funnel (see two examples in Figure 4). In this region, the intensity of the stray light tapers off gradually because of shadowing by the high OD funnel region.

**Figure 4:** Examples of model OD curves fitted to experimental OD profiles taken from raw projection images.
3. Discussion
The simple assumption of uniform stray light in each region of the image in the model accurately fits the optical behaviour except in the penumbra. To fit this region requires a more sophisticated treatment of how stray light behaves near the interface between regions of strongly differing OD. Perhaps a Monte Carlo treatment of this region could provide this.

Doming is explained by the fact that in the funnel phantom, the background gel outside the funnel and the baseline reference phantom were made with an OD higher than was used for the background and baseline reference in the finger phantom [5] and so the effect of stray light in these two regions cannot be ignored. The result is that OD in the baseline and background gels, is also underestimated. Moreover, there is a hidden dishing artefact in the baseline reference data which when divided out of the phantom data has the effect of increasing the apparent OD in the middle of the funnel which partially compensates for dishing in the funnel. For small cross-sections of the funnel where the dishing is weak, dividing by the dished baseline results in doming.

4. References
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