Initial experience with optical-CT scanning of RadBall Dosimeters

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Abstract. The RadBall dosimeter is a novel device for providing 3-D information on the magnitude and distribution of contaminant sources of unknown radiation in a given hot cell, glovebox, or contaminated room. The device is presently under evaluation by the National Nuclear Lab (NNL, UK) and the Savannah River National Laboratory (SRNL, US), for application as a diagnostic device for such unknown contaminants in the nuclear industry. A critical component of the technique is imaging the dose distribution recorded in the RadBall using optical-CT scanning. Here we present our initial investigations using the Duke Mid-sized Optical-CT Scanner (DMOS) to image dose distributions deposited in RadBalls exposed to a variety of radiation treatments.

1. Introduction

The RadBall dosimeter, under development by the NNL, consists of a baseball-sized sphere of PRESAGE™ encased in a tungsten collimating shell (figure 1). PRESAGE™ is a radiochromic plastic material that has been investigated previously in the context of external beam radiation therapy (Sakhalkar et al [1], Adamovics et al [2]). The collimating shell is of 5-10mm thickness (depending on application) and is punctuated by an array of uniformly spaced holes that allow radiation tracks to penetrate into the dosimeter. After the RadBall is exposed in an unknown radiation field, the tracks deposited in the dosimeter can be imaged using optical-CT (first shown by Doran et al [3]), and the distribution and magnitude of unknown contaminant sources can be estimated by a back-projection of the measured radiation tracks to the surfaces containing the contaminant (walls, ceiling etc). Further details of the rationale of RadBall application are presented in an accompanying abstract (Farfan et al. [4]). The purpose of this article is to describe our initial experiences developing an optimized optical-CT scanning technique to image the radiation tracks in the RadBall dosimeters.
Fig 1: a) photograph of a disassembled RadBall showing the baseball sized PRESAGE™ sphere sitting inside the tungsten shell. The top part of the shell is removed for clarity. b) a coronal slice through a 3D optical-CT reconstruction of a RadBall irradiated by two 1cm² beams incident through the upper part of the dosimeter as indicated by red arrows.

2. Materials and Methods
RadBalls were scanned in the Duke Mid-sized Optical-CT Scanner (DMOS), illustrated here in figure 2, and with the commercial MGS scanner for independent comparison. Parallel ray geometry was established using a matched telecentric light-source and lens. The telecentric light source produces a nominally parallel beam. Rays then pass through the aquarium containing refractive index (RI) matched fluid containing the RadBall (not shown in figure 2) and are collected by the telecentric lens. An aperture on the lens enables a variable acceptance angle from ~0.2-15 degrees of light rays used in image formation. Light rays deviating from the optical axis more than the acceptance angle are excluded from the image. The CCD camera mounted to a 0.08X telecentric lens and had a 1040x1392 pixel array. As the field of view is ~11cm, each pixel corresponds to ~0.08mm. Projection images were resampled to 0.5mm resolution to improve noise and maintain more manageable file sizes.

Fig 2: a) Duke Mid-sized Optical-CT Scanner (DMOS)

A matched telecentric source and lens create an efficient, non-magnifying imaging beam, the projection of which through the RadBall dosimeter (not shown – but would be placed on the stage) enables measurement of the line integrals of attenuation at each pixel in the image. In principle, any scattered light is rejected from image formation in accordance with the acceptance angle of the lens.

2.1. Preliminary tests on RadBall irradiated with a Linac
Initial testing was done by irradiating two RadBalls without the collimating outer casing with beams from a medical linear accelerator. Tests were designed to determine basic feasibility, and performance capabilities regarding data quality (e.g. edge and ring artifacts), spatial resolution, noise, ability to discriminate different energies (6 and 15MV) etc. The first RadBall was irradiated with a simple two-beam arrangement as shown in figure 1b. Both beams were 1 cm²; one was 6MV and the other 15MV. The second RadBall was irradiated with 6 – 4 mm² 6MV beams (doses of 6, 4, 2, 1, 0.5, and 0.25 Gy)
that intersected at the isocenter positioned at the base of the RadBall. The optical-CT scanning procedure for both RadBalls included acquiring 360 projection images acquired at 0.5 degree increments. An average of 10 images was acquired at each projection angle. Flood and dark correction images were created from an average of 200 images. The total acquisition time was approximately fifteen minutes.

2.2. Proof of concept RadBall irradiation
The promising results from the preliminary tests in 2.1 warranted an evaluation of a more realistic application of the RadBall dosimeter. A complete assembled RadBall (N10-2 complete with external collimating housing) was irradiated from multiple directions with a Co-60 source. The source was incident on the RadBall from 6 equi-spaced angles (60 degrees apart), and each angle delivered a dose of ~1Gy in-air at the center of the RadBall. 14 RadBalls were irradiated in various other geometries.

3. Results and Discussion
An example of a single projection of an unirradiated and irradiated RadBall, as seen through the DMOS scanner, is shown in figure 3a and b respectively. Careful matching of the refractive index of the fluid in the aquarium to that of the RadBall reduced the edge artefact to a narrow peripheral band. Although the quality of the projections is good, imperfections (particulates, scratches etc) are visible on the surface and within the RadBalls. New manufacturing processes have greatly reduced these sources of noise.

3.1. Preliminary RadBall tests
A single coronal slice of the 2-field irradiation is shown in figure 4a. Percent depth-dose curves along the dotted red lines are shown in figure 4b. Both curves have been normalized to their respective values at the expected depth of maximum dose. Good high-resolution visibility of beams and intersection point are achieved with minimal edge effects. The lack of pronounced edge effects is a function of good RI matching between the fluid and PRESAGE™, and is an advantage of the PRESAGE™ material that does not require an external container, enabling dose measurement close to the surface. Useful PDD curve data is achieved and enhanced with a simple median filter. Notable features of the PDD curves are that the dose build up is clearly visible in both beams, enabling a distinction of the different beam energies.
A representative and illustrative 2D reconstructed slice of the RadBall irradiated with 6 - 4\text{mm}$^2$ pencil beams is shown in figure 5a, with corresponding partially transparent rendering of the entire 3D data cube in figure 5b. This data set is a subtraction of the (post)-(pre-scan) images. The high spatial resolution of the scanning system is evident from these images, as the 4x4mm beams are clearly distinguished. The 6, 4, 2, 1 and 0.5 Gy beams are easily distinguished. The 0.25 Gy beam is faint but can just be observed.

![Fig 5 (a) single reconstructed axial slice of the six 4 mm$^2$ beam irradiation. (b) A partially transparent rendering of the entire 3D dose cube. (c) A single reconstructed slice of the proof-of-concept irradiation of a RadBall irradiated in the collimator housing.]

3.2. Proof of concept RadBall irradiation
A single slice of the 3D data cube reconstructed for the RadBall irradiated in the collimator housing is shown in figure 5c. A more pronounced edge effect is observed with this RadBall presumably due to a poorer RI match. A higher background dose was also delivered to this RadBall due to its exposure in a broad high energy Co-60 beam (1.2 MeV). The increased transmission of radiation through the holes in the collimator are still clearly visible against this background, lending support for the viability of the RadBall approach.

4. Conclusions
The DMOS scanner is demonstrated to achieve good visualization of the radiation tracks deposited in the RadBall. Critical issues to achieve high quality data include good RI matching, flood and dark corrections, fine control of acceptance angle in the telecentric imaging chain, accurate modelling of spectral effects on the light source (see accompanying abstract [5]). The preliminary experiments demonstrated that energy resolution is feasible provided PDD curves can be obtained. The proof-of-concept irradiations of the complete RadBall assembly showed that the DMOS scanner has sufficient spatial resolution and sensitivity to warrant next step investigations: field studies.

References
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