**RADBALL™: a new departure for 3-D dosimetry**

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**Abstract.** This paper describes a new device, RADBALL™ for mapping environmental radiation fields, as found in the area of nuclear decontamination. The system consists of a specially shaped PRESAGE™ dosimeter, which sits inside a custom-designed lead collimator. This is imaged using optical CT to yield data from which the position of either point sources or extended objects may be reconstructed. The principle of the technique is explained, simulations and preliminary data are given and the current design of the dosimeter and collimator are presented.

**1. Introduction**

To date, the primary use of spatially resolved 3-D radiation dosimetry has been within the medical community, for simulating the dose deposited during radiotherapy treatments. However, the concentration of the 3-D dosimetry literature in this area and, consequently, the relatively restricted set of journals in which the material is published, have meant that potentially important applications in other industrial fields have not yet been explored.

As the cost of oil continues to rise inexorably and amid the current fears over energy security, the UK and other countries around the world are currently experiencing a renaissance in the nuclear industry. Despite this, a continuing area of public concern is the decommissioning of nuclear facilities at the end of their lifetime. Although many problems of decontamination have now been solved, there is still a need for 3-D position-sensitive detectors of radiation for the location of unidentified sources. Typical environments in which such devices would be useful are glove boxes, active cells and other confined spaces, in which the level of radiation might be high or access might be limited. Whilst the concept of 4π Compton imaging, using sold state detectors, is well known and a number of experimental implementations have been demonstrated in the research literature [1,2], such systems may not be suitable for use within the nuclear industry. Ideally, a device should be cheap, robust, stable against extremes of temperature and remotely deployable, without the need for connecting wires or intervention during the measurement process.
This paper introduces R\textsc{AD}B\textsc{ALL}TM, a solution to the problem described above. Subsequent sections describe the concept, give the results of simulations to test the idea, present preliminary data and show pictures of the current device.

2. Concept
The PRESAG\textsc{E}TM dosimeter formulation [3] is well known for being physically robust and is stable during a prolonged irradiation period and at elevated temperatures. It exhibits negligible chromophore diffusion and has good post-irradiation storage properties. It has a linear response over a wide range of doses (up to several hundred Gy) for the energies of incident radiation so far tested. Unlike polymer gels, PRESAG\textsc{E}TM appears, in tests to date, to be entirely insensitive to oxygen. It is thus an ideal material for applications in the nuclear industry.

The RadBall\textsc{TM} concept is illustrated in Figure 1. RadBall\textsc{TM} consists of the combination of an integrating radiation detector, made of PRESAG\textsc{E}TM with a custom built lead collimator. The device is deployed in the area which is to be mapped and radiation from the source passes through the holes in the collimator to expose the PRESAG\textsc{E}TM. If the source is discrete, then easily identifiable tracks will appear in the sample, whereas extended sources will give a more diffuse pattern. After optical CT
scanning, a map of the sources is reconstructed. For a set of discrete sources, this can be performed simply by tracing the distinct lines in the optical CT images back to their intersection point. If one is dealing with an extended source, then more sophisticated reconstructions are necessary.

3. Simulations and development of the lead collimator

In accordance with the basic principle for source location, as outlined above, software was written in IDL (ITT Visual Information Solutions) to simulate a lead collimator of the type proposed. A variety of case studies were simulated, demonstrating that it is feasible to identify distinct “tracks” in the dose distribution corresponding to radiation paths through the holes in the lead collimator. These simulations were further used to estimate a suitable size and separation for the holes in the collimator and inform the manufacturing process.

A particular concern was the need for a compromise between having the lead shell as thick as possible to provide the maximum shielding for regions away from the tracks, whilst maximising the solid angle subtended by each hole. In order to ensure that the device is sensitive to radiation from a variety of angles and thus operates like an ideal “pinhole camera”, the holes in the lead shell should be thin. However, if the collimator thickness is not great enough then its attenuation is small and we lose image contrast between the track regions and the nominally uniradiated regions. This compromise is energy-dependent, as the linear attenuation coefficient varies very rapidly in the region of interest (hundreds of keV – several MeV).

Figure 2 illustrates these points, using the source configuration adopted for a hypothetical irradiation by two photon-emitting point sources. These are positioned 5 cm perpendicularly on either side of a radial line from the centre of the sphere, at a distance of 10 cm from the sphere centre. Holes of diameter 2 mm and separation 10 mm are drilled in the lead shell. Figure 1(a) illustrates the case of a relatively low energy photon at 433 keV ($\mu = 2.18 \text{ cm}^{-1}$), whilst Figure 1(b) is the corresponding case for $^{60}$Co ($E = 1.2 \text{ MeV}, \mu = 0.635 \text{ cm}^{-1}$). The reduced image contrast in 1(b) is evident, but the images would still be suitable for source location. Moreover, by choosing materials other than lead for the absorbing collimator one can obtain increased values of linear attenuation coefficient.

Figure 2: Simulation of one plane through the collimator for two different energies (a) 433 keV; (b) 1.2 MeV. Note the reduction in image contrast as the 5 mm thickness of lead gives lower shielding at increased energies. (c) variation of the linear attenuation coefficient of lead at different energies, showing the there is significant potential of optimising the device for different radioactive contaminants.
4. Preliminary experiments

Prior to the manufacture of the complex hemispherical dosimeter and collimator, the concept of RadBall™ was tested using a cylindrical PRESAGE™ sample of diameter 6 cm and height 6 cm. This was surrounded by a lead sheet of thickness 2 mm, in which a simple grid of 4 mm holes was drilled (four rows of 13 holes). It was placed in front of an X-ray tube, operating at 80 keV and 250 µA at two different distances, 10 and 20 cm with orientations approximately 90º apart. The dose rate delivered was 410 μGy s⁻¹ at 10 cm and 110 μGy s⁻¹ at 20 cm. In each case, the dose delivered was approximately 46 Gy, chosen in order to gain clear visualisation of the radiation tracks. It should be remembered that at this low energy, the linear attenuation coefficient is much higher than at therapeutic energies and the dose deposited decays very rapidly as it passes through the sample. This explains why it was possible to use as little as 2 mm lead, whilst the production version of RadBall™ uses 5 mm. The samples were imaged on the CCD-based scanner at the University of Surrey, using methods previously reported [4].

Figure 3 shows the results of the experiment. Clear tracks are seen both in the projection images and the reconstructed slices. Notice that the tracks do not appear to span the entire diameter of the dosimeter. There are three reasons for this: (i) At the proximal end of the track wall artefacts appear. In this case, since we are interested in knowing the exact distance of the source from the sample edge, it is helpful not to eliminate this from the image (which could be achieved by performing the standard processing method of data correction by a scan of the unirradiated dosimeter). (ii) At the distal end of the track, the signal has been strongly attenuated (see above). (iii) The two sets of tracks are not exactly co-planar and so a single slice image cannot show them both completely.

By considering two well-chosen planes, the position of the radiation sources may be reconstructed. An initial estimate, based on a “by eye” tracing (using the MacOS X medical visualisation application OsiriX for on-image measurements), gave 9.9 and 20.9 cm respectively as the distances from the dosimeter surface to the two sources respectively, in good agreement with the actual values. For this initial manual measurement, the errors in these measurements were estimated to be approximately 5%. However, further work is needed to develop automated software to perform this task, together with an objective estimate of the measurement error.
5. Completed RADBALL™ system and future work

Figure 4 shows the completed collimator, together with the custom-manufactured PRESAGE™ insert. Initial irradiations are underway. One issue that remains to be resolved is the length of time that the samples must currently be left in situ to receive enough dose to obtain successful images. This is being addressed by investigation of different formulations of PRESAGE™. It should be noted that one advantage of this industrial application over the medical dosimetry scenario is that there is no requirement for the dosimeter to be tissue equivalent. This allows a different set of elemental ratios to be introduced in the PRESAGE™ composition and hence may lead to dosimeters that are optimal for the requirements of industrial dosimetry.

References

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