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To cite this article: M A Bero and W B Gilboy 2004 J. Phys.: Conf. Ser. 3 261

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High-resolution optical tomography for 3-D radiation dosimetry with radiochromic gels

M A Bero¹ and W B Gilboy²
¹ Department of Radiation Protection, AECS, PO Box 6019, Damascus, Syria
² Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK

Abstract. Modern radiotherapy methods require sophisticated treatment planning and radiation dose delivery routines, which in turn demand stringent quality assurance. This paper describes recent advances in three-dimensional optical computed tomography (OCT) readout for radiation dosimetry in which a tissue-equivalent radiochromic gels is used to achieve submillimetre spatial resolution for (512)³ voxel arrays in readout times of about half an hour.

E-mail: ma-bero@scs-net.org

1. Introduction

Optical tomography is non-destructive technique capable of providing sectional imaging of an object by reconstructing optical information obtained from chosen slices through this object. This can be achieved by collecting a set of optical transmission measurements called ‘projections’ at different angles around the imaged object. The number of projections and angles used plays a significant role in the determination of the image resolution and it also governs the total time required for recording these images. In order to obtain a three-dimensional (3-D) measurement of an ionising radiation dose distribution a tomographic imaging system that applies non-ionising radiation is preferable. From the standpoint of 3-D dosimetry the key observation was that ionising radiation causes measurable changes in the magnetic properties of an aqueous medium that contains paramagnetic ions [1]. Magnetic resonance imaging (MRI) was therefore the main initial candidate. MRI is a relatively slow, complex and expensive technique that has hampered the widespread use of this 3-D dosimetry method. The development of an alternative more practical technique, for example the use of light to obtain a tomographic image of the radiation dose distribution in certain host materials was then considered [2]. The optical method was introduced into three-dimensional radiation dosimetry as a fast, convenient and inexpensive dose readout method. Our approach, however, differs considerably from that proposed by Gore and his research group. First it uses a radiation sensitive transparent gel that changes its light absorption properties when exposed to ionising radiation [3]. A fully automated scanner that uses normal visible light beams and a CCD camera capable of recording a full two dimensional projection in a single exposure was constructed and used for 3D dosimetry [4]. This resulted in an ultra-fast true optical tomography imaging system.
2. Optical tomography system

Since the gel sample has refractive index close to that of water; it is mounted on a turntable inside a water-filled parallel-sided Perspex tank to minimise optical distortions caused by refraction and reflection, and also to ensure that the scanning light beams suffered no discontinuity as they entered and exited the dosemeter sample. Light source was placed at the focus of a condenser lens to form a broad parallel beam of light, which enters the tank at right angle, and after passing through the gel sample casts a shadow image onto a diffusing screen placed outside the far wall. This 2-D image is a simple projection of the irradiated regions of the gel dosemeter, and by rotating the sample through a known angle; many such projections can be recorded by a CCD camera linked to a personal computer. Each point in the 2-D projections corresponds to the line integral of absorption along the associated light beam, and the tomographic reconstruction yields 3-D distribution of absorption which is related to the absorbed dose distribution in three dimensions.

System layout and components are illustrated in figure 1, and its performance is demonstrated by the presentation of two practical experiments. A mercury discharge lamp, which gives a series of bright spectral lines matching interesting regions of the absorption spectrum of the gel, was employed and band-pass filters are used to select particular lines. Non-uniformities across the light beam are corrected by taking a single “sample out” reference projection at little extra cost in total readout time. The CCD detector has a 768x536 pixels whose signals are measured with a 10-bit frame-grabber card in 50 ms per frame; to reduce electronic noise 20 frames per projection were averaged. In practice about 400 projections, each of 512x512 pixels, were recorded to yield 100 contiguous slice images, each 140 µm thick, by filtered back-projection in a total scanning time of 38 minutes. Severe ring artefacts appeared in the first images principally due to systematic response variations in the CCD pixels but they also arise due to granularity in the simple shadow screen employed. The first of these can be virtually eliminated by “wobbling” the phantom or the CCD to average the signals over several neighbouring pixels. Similarly moving the screen up and down averages out the granularity.

The Ferrous Xylenol Gelatin (FXG) radiochromic gel was used both for the development of the OCT technique as well as for investigations designed to assess its use as detector for 3-D dosimetry. In almost all these experiments FXG gel composition was kept the same as reported in an earlier publication [4]. For OCT imaging experiments gel dosemeters were formed into a cylindrical shape inside thin-walled transparent plastic vessels sealed with airtight caps. These were 5.5 cm in diameter and 7 cm high, which falls well within the field of view of the OCT scanner, which is currently about 10 cm diameter. A gel sample is made following the usual procedure and while it is still in the liquid phase it is poured into a clean container which is then placed in a refrigerator at a temperature of about 4°C for a period of time between one hour and several days.
3. Results

The OCT scanner was employed in various experiments aimed to characterize it and to verify its capability to read out radiation dose distribution with high-resolution measurements. Some of these experiments were designed for the purpose of tuning the scanner performance in order to achieve the best possible results, and also to compare the quality of our OCT images with other reported OCT approaches used for 3-D dosimetry [5].

In the first experiment, FXG gel sample was irradiated with a 0.5 cm wide collimated X-ray beam 20 mA and 100 kVp for 10 minutes at two different positions perpendicular to the sample rotation axis. The first optical imaging test was started almost immediately after irradiation finished. It usually takes a few minutes to fix the sample accurately in position and to select the required parameters in the acquisition program. However this initial short delay helps in obtaining more accurate readings since the colour change reaction requires a few minutes to completion in the irradiated section of the gel. This irradiated sample was readout for two different image pixel resolutions in order to reach the best compromise between image quality and the time required to acquire and reconstruct the tomographic data obtained. Figure 2 shows slice images selected from the middle of the sample at the level corresponding to the X-ray beams to demonstrate the effect of changing pixel resolution.

![Figure 2](image_url)

**Figure 2.** OCT slice images of a crossbeam radiation pattern in an FXG gel sample, for different values of the system pixel resolution; (a) 256×256 and (b) 512×512.

Fading in the dose pattern is mainly due to increasing the number of pixels used to obtain averages of the signal, however diffusion of ferric ions and colour molecules may occurs in the FXG system with increasing time delay after irradiation. Better quality CCD detectors are becoming commercially available at the present time, so pixel resolution could be increased substantially if required. It may even be possible to obtain a two dimensional CCD array that is as large as the field of view (FOV) of our current OCT system which is about 10×10 cm². In that case there would be no need to collect shadow images via a lens system but rather it would be possible to obtain transmission images directly with a big gain in light collection efficiency.

In the second example FXG gel sample was irradiated for 10 minutes along the axis of the cylindrical vessel with X-ray beam that has the same parameters mentioned above. Image reconstruction was via the filtered back-projection method, and examples of reconstructed slice images are shown in figure 3 below.

Image (a) is the top slice in the sample and is nearest to the X-ray tube, and hence is the most intensely irradiated, (b) shows the dose distribution in a slice at the end furthest from the tube where the dose is much lower due to the fact that the X-ray beam is attenuated by a 7 cm thick layer of the detector material.
Figure 3. OCT images of a single X-ray beam. First and last slice images, (a) and (b) respectively, were acquired immediately after irradiation, (c) shows a sinogram corresponding to projection data for slice image (a).

4. Conclusions

The OCT is a simple, safe, cost-effective, easy to construct and operate imaging method, it should be considered as a strong competitor to other candidates for 3-D dosimetry. Practical convenience has great deal of importance in making the whole 3-D dosimetry system applicable in normal medical physics departments and small clinics. One of the most important characteristics of the OCT technique is its ability to map three-dimensional radiation dose distributions very rapidly, which is a key requirement for validating complex irradiation procedure. The use of a CCD array detector makes it possible to employ broad beam illumination that could cover the whole test phantom. The feasibility and potential of the OCT method was demonstrated, but at the same time some difficulties and drawbacks appeared. Some of these complications are intrinsic to the technique such as limitations of the detector material itself and problems associated with the containment vessel and readout hardware, but on the other hand lots of these hitches are related to the cheap components used and readily amenable to improvement. Also the software and programs utilized to control, acquire, reconstruct or visualize images can be further improved to reduce some artifact errors. Both the hardware used, particularly the CCD detector, and the software can be improved substantially to give even better 3-D dosimetry readout system than most other techniques available at the present time.

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