Creation of sophisticated test objects for quality assurance of optical computed tomography scanners

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Abstract. Optical computed tomography (CT) shows great potential for radiation therapy dose verification in 3D. However, an effective quality assurance regime for the various scanners currently available still remains to be developed. We show how the favourable properties of the PRESAGE™ radiochromic polymer may be exploited to create highly sophisticated QA phantoms. Five 60 mm-diameter cylindrical PRESAGE™ samples were irradiated using the x-ray microbeam radiation therapy facility on the ID17 biomedical beamline at the European Synchrotron Radiation Facility. Samples were then imaged on the University of Surrey parallel-beam optical CT scanner and were designed to allow a variety of tests to be performed, including linearity, MTF (three independent measurements) and an assessment of geometric distortion. A small sample of these results is presented. It is clear that, although the method produces extremely high quality test objects, it is not practical on a routine basis, because of its reliance of a highly specialised radiation source. Hence, we investigated a second possibility. Two PRESAGE™ samples were illuminated with ultraviolet light of wavelength 365 nm, using cheap masks created by laser-printing patterns onto overhead projector acetate sheets. There was good correlation between optical density (OD) measured by the CT scanner and the expected UV “dose” delivered. The results are highly encouraging and a proposal is made for a scanner test regime based on calibrated and well characterised PRESAGE™ samples.

1. Introduction
The technique of optical computer tomography (CT) [1-2] has shown great potential for the mapping of radiation doses in three dimensions, as well as in 3-D biological imaging [3]. However, it is clear that careful attention to quality assurance (QA) is necessary if the long term aim of the technique is to be able to provide any form of “gold standard” for 3-D dose mapping. In other fields of medical imaging, particularly diagnostic scanning, QA is now routine, with prescribed imaging protocols and specialist companies providing QA phantoms. Whilst a number of academic studies e.g., [4-6] have previously used phantoms to characterise properties of optical CT scanners such as linearity and geometric distortion, the degree to which sophisticated test objects can be manufactured mechanically
Figure 1: Reconstructed slices from three PRESAGE™ phantoms irradiated at ESRF: (a) Sample 1: 7 10 × 10 mm² squares 0.5 to 15 Gy; (b) Sample 2: 19 5 × 5 mm² squares 0.5 to 30 Gy and 5 sinusoidal patterns: (A) 3 lp/mm, (B) 2 lp/mm, (C) 1 lp/mm, (D) 0.5 lp/mm, (E) 0.25 lp/mm; (c) Sample 3: resolution test pattern of different line widths, each depositing 6 Gy: (A) 1 mm, (B) 0.5 mm, (C) 0.25 mm, (D) 3 mm, (E) 2 mm, (F) 0.1 mm, (G) 0.05 mm. Two 10 × 10 mm² squares were irradiated with 2 and 4 Gy respectively for calibration purposes.

Figure 2: Sample 4: (a, b) projection images from two angles; (c) single slice from the reconstructed 3-D image with markers corresponding to regions analysed in Fig. 5d.

Figure 3: Sample 5: Multipurpose geometric distortion mapping phantom: (a) typical projection image (b,c) reconstructed transverse slices at two different levels.
is limited. Nowhere is this demonstrated more graphically than in the quantitative validation of optical CT microscopy. The type of India-ink-in-gel phantom created by Sharpe et al. [3] from would not be suitable for verifying optical density values or assessing image distortion, but to construct something better mechanically would be an enormous technical challenge.

The radiosensitive polymer PRESAGE™ has a number of favourable properties, the most important for this work being mechanical strength (a solid rather than a gel), stability over the temperature range routinely encountered in clinical and research practice, and long-term stability of the dose pattern created by irradiation. Although the optical density values are not completely fixed, changes over time are predictable and can be calibrated. In this abstract we demonstrate how these properties allow the creation of robust samples of great sophistication via complex irradiations. We then suggest how, given appropriate calibrations, standard samples can be created at little cost by using UV irradiation. Finally, we propose a test framework for comparing different optical CT scanners, linked to a spectrophotometric standard.

2. Materials and Methods

2.1. Phantoms irradiated using synchrotron x-rays

Dose mapping was carried out using PRESAGE™ dosimeters in the form of cylinders of diameter 60 mm and height 60 mm, and calibration measurements were carried out with small PRESAGE™ samples supplied in standard 10 × 10 × 45 mm³ optical cuvettes. (Similar experiments, reported elsewhere, were also performed using PRESAGE microscopy samples with a range of diameters 20 mm and below.) Irradiations were carried out at the European Synchrotron Radiation Facility (ESRF) in Grenoble on the ID17 biomedical beamline. This beamline uses a “wiggler” source to produce an intense, highly collimated synchrotron x-ray beam from the 6 GeV circulating electrons. The x-ray spectrum covers the range 50 to 350 keV with a mean energy of 107 keV and peak at 83 keV [7]. The irradiations were performed using a “dose-painting” technique, by translating the samples through the beam to provide various patterns mentioned.

Five phantoms were created to allow the investigation of linearity, spatial resolution and MTF, and geometric fidelity of the scanner. In addition, the samples demonstrate the dose-integration properties of the dosimeter and allow the measurement of depth-dose curves. Sample 1 (Figure 1a) was composed of seven 10 × 10 mm² squares covering a dose range of 0.5 – 15 Gy. Sample 2 (Figure 1b) was inspired by the standard USAF optical test target (Edmund Optics NT54-803), which combines a linearity / absolute optical density test with an MTF test. The linearity test increased the number of squares to 19, each 5 × 5 mm², extending the dose range to 0.5 Gy – 30 Gy, whilst also allowing us to test the in-plane reproducibility of measurements by creating four squares each with dose 8 Gy. The MTF test was made from 5 regions of sinusoidally-varying dose with different periods, deposited using a macro to automate the ID17 goniometer and shutter. Sample 3 uses a different method to test MTF: it contains nine slit patterns, creating near-ideal line-pairs with spacings from 0.14 lp/mm up to 2.75 lp/mm. This sample illustrates graphically the enormous advantage of the synchrotron irradiation over a standard clinical linac, where field penumbras make it impossible to create well-defined areas of uniform dose at this scale without the construction of an intricate collimator [8]. Sample 4 (Figure 2) is a pattern of multiple irradiated fields, each with simple geometry, allowing us to test our assumption that the PRESAGE™ dosimeter is a perfect integrator. It also contains a number of “knife edge” structures that can be used for a further MTF analysis. Finally, Sample 5 (Figure 3) is a regular grid of 2 × 2 mm² square dots. The absolute location of these is known and hence we can determine very precisely whether the measured images contain any distortion. In our view this is a superior method to the needle phantom used by [4-5], because the dots are not opaque and so image artefacts are not created. The sample is further irradiated from the side. By such means, it is possible to create alternating layers that allow distortion in the z-direction to be calculated, too.
2.2. Phantoms irradiated using ultraviolet light

A severe criticism of the above work might be that one could not possibly base any realistic QA regime on samples that required a synchrotron for their creation. As an alternative, we sought to make use of the known UV sensitivity of PRESAGE™. This has previously been regarded as a problem and samples are routinely wrapped in black plastic to avoid unwanted exposure during experiments, transit and storage. To our knowledge, there have been no detailed studies of the dose-response of PRESAGE™ to UV.

A computer drawing package was used to create a pattern of seven squares, resembling Sample 1, having different grey levels between 100% (white) and 20%. This was laser-printed onto an overhead projector acetate sheet to form a UV mask. A second mask was created from part of a resolution test pattern (5 lp/mm to 12 lp/mm) [9], allowing us to investigate the spatial resolution achievable using a UV radiation. Masks were placed on top of cylindrical PRESAGE™ samples and irradiated for 20 minutes from the top with a uniform beam of 365 nm UV light of intensity 9.95 mW/cm² using the lamp of a mask aligner.

2.3. Imaging methodology

All samples were imaged using the University of Surrey parallel-beam scanner. For these scans, 800 projections of matrix size 512 × 512 pixels were acquired and reconstructed into a stack of 512 × 512 axial images using filtered back projection using in-house software written in IDL.

Figure 4: The UV irradiation setup. (a) Test pattern of seven squares (10 × 10 mm²) of different transparency levels; (b) resolution test pattern (5 lp/mm to 12 lp/mm); (c) PRESAGE™ during irradiation was covered with black plastic except at its surface where the mask was located; (d) optical CT image of UV phantom created using mask in (a); (e) relationship between grey level in mask definition file to optical CT output, illustrating that a good calibration should be possible.
3. Results and Discussion

Optical CT images of the various samples are shown in Figures 1−4. A variety of tests was performed on the 3-D images, of which (for reasons of space) just a small selection of results is shown in Figure 5. The samples are suitable for performing linearity, MTF, geometrical distortion and signal-to-noise analysis, together with measuring the depth dose in both x-ray and UV samples (the latter being, to our knowledge, a novel result). Further samples demonstrated the artefacts resulting from scanner (but not dosimeter) saturation and could make quantitative measurements of this effect to compare with theory.

We propose that an appropriate calibration regime would consist of the manufacture of a number of such samples from a single batch of PRESAGE\textsuperscript{TM}, together with a set of cuvettes (one per sample). The cuvettes (calibrated using a spectrophotometer) would accompany samples, experiencing the same temperature history. Phantoms would be imaged at regular intervals and exchanged between sites.

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