How to perform an optical CT scan: an illustrated guide

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Abstract. In this article, which accompanies one of the morning “refresher” sessions at the IC3DDose 2012 conference, a workflow for optical CT scanning is described and the following steps in that workflow are illustrated: sample positioning, refractive index matching, the importance of apparatus cleanliness to the imaging process, the pre-scan and image reconstruction and post-processing.

1. Introduction
There is by now a considerable body of literature concerning the methodology for performing 3-D radiation dosimetry. As part of the IC3DDose 2010 “refresher course”, I discussed in [1] two of the most widespread image acquisition techniques, Magnetic Resonance Imaging and Optical Computed Tomography (CT), and attempted to distil the existing research into a set of “hints and tips” to enable newcomers to the field to avoid common problems. This article is designed to be complementary to [1] and aims to provide a step-by-step guide to the process of acquiring an optical CT scan, illustrating the key procedures involved [2, 3].

2. Procedure for optical CT scanning
Figure 1 shows the complete workflow for the scanning process. A number of tasks are performed prior to the scanning experiment (during scanner commissioning, on receipt of a new sample batch and prior to the start of a set of imaging experiments), whilst others should ideally be performed for each sample that is scanned.

2.1 Sample positioning
An important requirement of the experiment as a whole is the ability to load a sample into the scanner at a consistent position and rotation angle. This turns out to be non-trivial; the various different scanners available commercially, and those developed in-house by research groups in this field, all use different systems for locating the sample correctly. A selection of these is shown in figure 2. As part of initial system commissioning and of on-going quality assurance procedures, it is advisable to investigate sample positioning, by repeatedly inserting the sample, rotating to a predefined angle, acquiring a projection image and then randomly resetting the position of the rotation stage before removing the sample. Forming subtraction images is an ideal way of revealing any differences in position of features in the projections.

2.2 Refractive index (RI) matching
Standard methods of optical CT, using either parallel-beam or cone-beam reconstruction make assumptions about the path of the light rays through the apparatus. Typically, the reconstruction algorithm does not take account of any deviations in the ray path brought about by refraction at the
boundary between the sample and the surrounding medium. Any discontinuity in RI across this boundary leads to deviation of the light rays and “imperfect” data. This, in turn, gives rise to the well-known “wall artefact”. At a very low level, this artefact can be helpful, marking the sample boundary on images. However, as was shown in [4], if uncorrected, the artefact can lead to a significant “baseline roll” that extends much further into the sample than expected and seriously impacts on the quantitative nature of the scan. Polymer gels have refractive indices relatively near that of water and these can be accessed via mixtures of either glycerol (glycerine) or ethylene glycol with water. In each case, the additives are miscible in all proportions, and lead to RI ranges from 1.33 – 1.39 and 1.33 – 1.43 respectively. The exact RI value for any given sample will depend on a number of factors, including its composition, its temperature (hence the need for good equilibration with the bath of matching liquid) and, for polymer gels, the quantity of dose it has received.

Figure 1: Procedure for performing an optical CT scan.

Figure 2: Different scanners have different ways of ensuring that the sample is positioned repeatably: (a) the Modus Vista uses a specially designed clamp to grip the top of the sample jar, with stepper motor providing the sample rotation from the top; (b) Octopus from MGS fixes the sample to a rotating platform; (c) Brady et al. use a sample that is moulded to fit in a unique place in the Duke University scanner — image from [2].
By contrast, the solid plastic radiochromic dosimeter PRESAGE® has a much higher RI of approximately 1.503 and matching can be achieved here with different combination of liquids. Previous research has used dibutyl and diallyl phthalates, but these a relatively toxic and must be
handled with care, so we now prefer to use a mixture of 2-ethylhexyl salicylate (RI ≈ 1.502) and 4-methoxycinnamic acid 2-ethylhexyl ester (RI ≈ 1.54), supplemented by small quantities of mineral oil (RI ≈ 1.48) if the mixture RI needs to be reduced significantly. There remain inconveniences caused by the length of time it takes to mix the samples to achieve good matching throughout and the non-solubility in water of all of these chemicals, making disposal of used materials and cleaning of the apparatus an issue. Figure 3 follows the stages of a typical experiment to determine the optimal matching liquid composition. Note especially the exquisite (but unwanted) sensitivity to very small changes in refractive index, and the addition of a dye to the liquid, for the reasons outlined in [1].

![Figure 3](image3.png)

**Figure 3:** The stages of a typical experiment to determine the optimal matching liquid composition.

2.3. **Cleaning**

It is hard to overestimate the importance of maintaining the cleanliness of an optical CT scanner. Whilst many potential artefacts can be removed from the final reconstructed optical-CT images by judicious post-processing of the data, eliminating the problems at source will provide much higher quality input data into the system. Figure 4 shows an extreme example of the sort of problems that can occur and which were too severe to be entirely corrected by the pre-scan procedure below.

2.4. **Pre-scan**

Figure 5 shows an example of scans of a PRESAGE® sample before and after irradiation. The pre-scan serves three functions. Firstly, it allows us to calibrate the light-field provided by the scanner [5], which will typically not be entirely homogeneous, showing either a smooth variation or a set of isolated imperfections (Fig. 4a). Secondly, the pre-scan enables sample-specific features to be removed from the images. These fall into two categories: (i) Wall effects and baseline roll due to residual RI mismatch can either simply be subtracted, or can be modelled, potentially improving the SNR of the final image. (ii) Sample imperfections causing optical artefacts that are constant between the two scans can potentially be removed by subtracting the reference pre-scan. However, this voxel-by-voxel correction does require excellent reproducibility of sample positioning. The third function of the pre-scan is to provide the baseline map of the sample’s optical density. Once this has been subtracted from the final post-irradiation data, what is left is a map of the change in optical density induced by the radiation and it is this quantity that is related to the absorbed dose.

![Figure 5](image5.png)

**Figure 5:** Example of reference pre-scan and corresponding post-irradiation scan — image from [3]
The pre-scan procedure has several pitfalls. The most important is that it is difficult to manage on a shared system. The University of Surrey group has worked on several projects that would have involved long delays between pre- and post-irradiation scans (e.g., low-dose-rate brachytherapy, with an exposure time of several weeks and synchrotron irradiations in which several days’ travel to the irradiation facility were required.) It is not always possible to guarantee that the equipment remains in the same state between pre- and post-scans. Typical issues are: changes in the incident light intensity (usually correctable); changes in field-of-view and focus (particularly challenging to account for when the system has manual lens adjustment); and changes in the refractive index matching liquid or additional contamination on the surfaces of the matching tank. Under these circumstances, we have found that it is useful to acquire a light-field scan (i.e., one with no sample present) to match each sample scan. In addition, it is also beneficial to acquire a scan with no light input to the camera (e.g., with lights off and lens cap on), in order to measure the so-called “dark-current image”. This information may be used to improve the reconstruction of the data [5]. Together, the light- and dark-field images allow one to perform a minimal set of corrections for the characteristics of the scanner, which provide a “basic image” that can be supplemented by further post-processing if sample-specific data become available. A further issue to be aware of is the need to monitor and correct for changes in the samples that are not related to radiation exposure. In another abstract to be presented at IC3DDose 2012 [6], we describe the effect of light on PRESAGE ® samples. However, these concerns apply equally, for example, to auto-oxidation of Fricke gels [7].

![Image of the Clarity application](image.jpg)

**Figure 6:** The Clarity application, written by the author at the University of Surrey, and running within the IDL (Interactive Data Language, Excelis Visual Information Solutions, Boulder, CO) data processing environment, is a typical example of the in-house image reconstruction solutions available.
2.5. *Irradiation and post-irradiation scan*

For the reasons outlined above, sample irradiation and subsequent scanning should ideally be carried out as soon as possible after the pre-scan, and the post-irradiation scan should use identical parameters to the reference.

2.6. *Image reconstruction and post-processing*

These two areas overlap and different authors will have different opinions as to the extent to which image post-processing and enhancement are part of the reconstruction process itself. The major steps in the reconstruction are reforming the individual projections into a set of sinograms (Figs. 4b and 4e), filtering the sinograms, and performing back-projection, the mathematics of which is described in many popular texts, including [8]. Typical post-processing tasks might include artefact removal and image enhancement by median filtering. Finally, some form of calibration must be performed to convert the optical density values returned by the scan into dose.

There is currently no “standard” software for reconstructing 3-D dose maps using optical CT, each research group and manufacturer having developed their own processing environments. A typical example is shown in figure 6. It is the author’s view that there would be considerable benefit for optical CT researchers to establish a working party to explore the creation of a standardised “community tool” that incorporates best practice and the most efficient reconstruction algorithms available. Such a tool could be designed to accept data from all the major groups and commercial scanners and would be complementary to specialist developments from individual groups. It would serve as a quotable “application of reference”, against which other software could be compared.

3. **Conclusion**

Unlike the case of MRI, image acquisition using optical CT is still not entirely a “push button” technology, although manufacturers and groups in the field are moving steadily towards this position. This article has outlined the major steps of the workflow involved

4. **References**

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