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Polymer gel dosimetry using x-ray computed tomography: investigation of the effect of reconstruction technique

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Abstract. X-ray computed tomography (XCT) imaging of gel dosimeters is a promising technique that may make gel dosimetry more practical for medical physicists to use clinically. One of the issues limiting its use is the dose resolution of the system, which is determined by the system’s noise and ability to resolve low contrast objects. Alternative reconstruction of CT data is shown to approximately halve the minimum detectable change in signal and increase, by up to double, the signal to noise ratio for small low contrast objects when compared with the vendor reconstruction. This has the potential to reduce the number of averages required in XCT gel dosimetry imaging protocols as well as improving dose resolution.

1. Introduction
The need for a suitable 3-D dosimetry tool for the verification of complex clinical techniques such as intensity modulated radiation therapy (IMRT), stereotactic radiation therapy (SRS and SRT) and volumetric modulated arc therapy (VMAT) has become much more evident in recent times. These techniques can produce highly conformal, localised dose distributions that need to be verified in three dimensions (3D). However the majority of methods used to verify these treatment techniques rely on one dimensional (e.g. ion chambers) or two dimensional (e.g. film) detectors [1, 2, 3].

Polymer gel dosimetry has been proposed and is now being used to clinically verify complex 3D dose distributions.

X-ray computed tomography (XCT) is a relatively new technique first proposed and demonstrated by Hilts et al in 2000 [4]. It has the potential to provide a practical solution of being more accessible and cheaper to use. Trapp [5] gave theoretical scan parameters appropriate for CT imaging of polymer gel dosimeters and the technical considerations involved in implementing XCT imaging of polymer gel dosimetry was discussed by Hilts [6].

There have been two areas of research for decreasing dose resolution and increasing sensitivity of the XCT gel dosimetry system. The first area is the use of spatial filters to remove some of the noise and improve the signal to noise ratio of the CT images by Hilts and Jirasek [7, 8]. The second area of research is investigating the change in the attenuation properties of polymer gels due to radiation exposure with the aim of increasing the Hounsfield unit (HU) response per Gy. Trapp, et al [9, 10, 11, 12, 13, 14, 15, 16] have investigated the effect of gel composition on the radiation induced
attenuation change in both normoxic and anoxic polymer gels. A summary of CT dose response for studied polymer gel dosimeters is given by Hilts [17].

The reconstruction algorithm, potential methods of maximising low contrast resolution and the sensitivity of the system have not been investigated in detail. This work compares images produced by the vendor reconstruction algorithm with images reconstructed by alternative methods.

2. Materials and Methods

2.1. Hardware

Two phantoms were used to investigate the reconstruction algorithms: the Siemens quality assurance (QA) phantom supplied with the CT scanner and a Catphan 600 phantom. The Siemens QA phantom contained a section of uniform density that was able to be extended off the end of the bed. The Catphan 600 phantom is made up of 4 modules designed to be used for quality assurance of x-ray CT scanners. The specific contents of each module are described in the Catphan 600 manual and is available from the manufacturer’s website [18]. The specific modules used were:

- Module CTP404; relative electron density \( \rho_e \), slice width, circular symmetry and signal to noise ratio.
- Module CTP486; uniformity module,
- Module CTP515; sub-slice and supra-slice low contrast resolution,
- Module CTP528; high contrast spatial resolution,

The CT scanner used to acquire the raw data and vendor images was a Siemens Sensation 16 PET/CT scanner. The parameters used for scanning the phantoms were 120kV, 320mAs, 3mm slice thickness using a 16 slice helical technique with a feed/rotation of 6.6mm. The vendor reconstructed images were exported using the Dicom format while the raw projection data was exported in a Siemens proprietary format based on the Dicom format.

2.2. Software

The third party reconstruction software ran in IDL and was designed to reconstruct the raw CT transmission data contained in the Siemens format. The program reconstructed the transverse slices using either filtered back projection (FBP) with one of the filters described in [19] (analytic method) or a maximum likelihood gradient ascent algorithm, based on optimisation transfer [20, 21, 22] (iterative method). The basic reconstruction process was to (i) import projection data and extract necessary header information; (ii) extract fan beam sinogram over region to be reconstructed; (iii) convert fan beam to parallel beam sinogram (made up of 672 detectors by 1160 angles); (iv) reconstruct using analytic or iterative algorithm and (v) export

3. Results

Using the vendor reconstructions as a reference, the central slice from each of the Catphan modules and a uniform slice of the Siemens QA phantom were reconstructed. Seven sets were reconstructed using FBP, one for each of the available filters, and twelve sets were reconstructed using ML with the number of iterations set between 7 and 30 and the number of subsets set to either 20 or 40 (corresponding to 29 angles per subset and 58 angles per subset respectively). Because the sinogram was unable to be modified without affecting the resulting reconstruction quality, the images were reconstructed using all 672 detectors and 1150 angles producing reconstructions with dimensions 672 \( \times \) 672 pixels. A representative image from each reconstruction method is displayed in figure 1 of the CTP515 low contrast module.

The reconstructed images were analysed in the way recommended in the Catphan manual [18]. The change in contrast with reducing distance between objects is known as the modulation transfer
Figure 1. Reconstructions of the CTP515 module; (a) FBP using rectangular filter, (b) ML using 7 iterations and 40 subsets, (c) Siemens reconstruction using the H31s (standard) filter.

function (MTF) and was determined using the high contrast line pairs in module CTP528. Contrast is defined as

$$\text{Contrast} = \frac{\text{ROI}_{\text{max}} - \text{ROI}_{\text{min}}}{\text{ROI}_{\text{max}} + \text{ROI}_{\text{min}}}$$

where the region of interest (ROI) was defined by the top of the first peak and the top of the last peak. The MTF is shown in figure 2(b) which plots contrast verse line pairs per cm. Module CTP404 with its inserts of varying relative electron density ($\rho_e = 0.0 – 1.87$) was used to compare the response of the reconstructions to $\Delta \rho_e$ (figure 2(a)). The third party software produced reconstructions in units of attenuation per pixel, which needed to be converted to Hounsfield units (HU) before being compared with the vendor reconstruction. This was performed using

$$\text{HU} = \frac{\mu_x - \mu_{H2O}}{\mu_{H2O}} \times 1000$$

where $\mu_x$ is the pixel value of an unknown substance and $\mu_{H2O}$ is the pixel value of water $\rho_e = 1.0$.

The low contrast module CTP515 (figure 1) contained six sets of objects with nominal contrast $0.3 - 1\%$ and diameters 2-15mm. None of the third party algorithms could adequately reconstruct ($SNR > 1.0$) the $0.3\%$ contrast objects. However the softer algorithms (such as FBP with Hamming filter and lower iteration ML) were able to adequately reconstruct the larger $0.5\%$ contrast objects and all were able to adequately reconstruct the $1\%$ contrast objects down to 4mm diameter. In comparison the Vendor algorithm was only able to reconstruct the $1\%$ contrast objects down to 9mm diameter with a $SNR > 1.0$.

Uniformity for all reconstruction methods was between $1 – 2\%$ with the variation explained by the characteristics of the different algorithms. Also there was very little difference between the uniformity of the Siemens QA phantom and the Catphan.

4. Discussion

The most obvious difference between the vendor and third party reconstructions is the size of the resulting images (compare figure 1(a) and (b) with figure 1(c)). This is because the third party reconstructions results in an image of the entire CT scanner field of view. This is unlike the Vendor reconstructions where cropping boundaries can be defined so that the resulting image is a $512 \times 512$ pixel reconstruction of the selected area only.

The MTF results (figure 2(b)) showed that both the vendor and third party reconstructions have the same limiting resolution of 6 line pairs per cm. However the vendor reconstruction does have
Figure 2. (a) Hounsfield unit response to objects with different $\rho_e^r$. (b) Change in contrast with reducing separation.

The advantage that for $\text{lp/cm} > 5$ the contrast is greater than that produced by any of the third party reconstructions. This is a result of the expansion of the vendor reconstruction with the smaller pixels (0.42mm per pixel verse 0.75mm per pixel) able to better image the two objects. The third party reconstructions with the best MTF was the rectangular FBP reconstruction while the worst MTF was produced by the 7 iteration, 40 subset ML reconstruction. Both these results are expected since the rectangular FBP filter does not smooth the data, while the 7 iteration 40 subset ML reconstruction is only just convergent which does not produce good MTF but has benefits in low contrast situations (for example figure 1(b)).

Figure 2(a) shows the Hounsfield unit response of the vendor and representative third party reconstructions. These are comparable along the lower half of the curve ($\rho_e^r \leq 1$) but are rather different in the upper half ($\rho_e^r > 1$) where the third party curves are more linear although two straight lines are still required to fit the data. Within the third party reconstructions the FBP filters all resulted in the same curve whereas the ML reconstructions resulted curves that differed by converged at higher iterations. With regards to the reconstruction of a uniform region, ignoring the differences between the algorithms, all the reconstruction give the same result.

The greatest impact of the third party reconstructions is in the reconstruction of the low contrast module (figure 1). This is where the third party reconstruction software has much to offer XCT gel dosimetry. Using the nominal contrast values the third party reconstructions have a minimum detectable change of $\sim 1\%$ compared with $2\%$ for the vendor reconstruction for a single 3mm slice. At the same time the third party reconstruction is reconstructing the objects with up to double the SNR compared to the Vendor reconstruction.

The improvements above are seen best with the smooth FBP filters (for example Hann) and the just convergent ML algorithm (for example 7it with 40 subsets). Therefore using a smooth filtered FBP or just convergent ML algorithm the impact on XCT gel dosimetry is potentially two fold. The smaller minimum detectable change means that the number of images required for averaging purposes is reduced for the same endpoint. And increase SNR has the potential to cause an improvement in dose resolution.

5. Conclusion
Third party reconstruction of raw CT projection data has been shown to approximately halve the minimum detectable change in signal and increase by up to double the signal to noise ratio for
small low contrast objects when compared with Vendor reconstructions. Taking these aspects into consideration, it may be possible to improve x-ray CT imaging of the irradiated gel dosimeter to such an extent that it may be possible to use it routinely in radiotherapy. The gel dosimeter would then be able to provide 3D dose evaluation of complex dose distributions created by the new complex modulated intensity x-ray techniques.

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