Image noise in X-ray CT polymer gel dosimetry

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1. Introduction

X-ray computed tomography (CT) can be used to extract dose information from irradiated polyacrylamide gel (PAG) dosimeters \cite{1–3}. This is possible due to a radiation induced density change that provides contrast in CT images. Although promising, the density change is small (~ 1%) and the contrast in PAG CT images is very low. Efforts are underway to better understand the response of polymer gel density to dose with the aim of developing gels more sensitive to read-out by CT. However, spatial resolution requirements limit the allowable density change \cite{4} and a CT gel technique will always be a low contrast imaging technique. Image noise is a critical factor in resolving low contrast images \cite{5} and in CT polymer gel dosimetry, noise directly impacts the dose resolution. This work investigates factors which affect image noise in CT polymer gel dosimetry, discusses techniques that can be used to further improve image noise and provides overall recommendations for the CT imaging of polymer gels.

2. Experimental noise measurement

A GE HiSpeedCT/i CT scanner (GE Medical Systems, Milwaukee, USA) was used for all CT imaging. Images were obtained of cylindrical water filled phantoms to mimic the density of polymer gel dosimeters. Scan parameters (as shown in table 1) were varied independently from a set of reference parameters (bolded) to access the dependence of noise on each parameter individually.

For each set of scan parameters, two images were taken in order to remove artifacts by background subtraction. The standard deviation in CT number ($\sigma_{\text{N}_{\text{CT}}}$) was extracted from a region (21×21 pixels) at the centre of the final images. Phantoms of three different diameters (3, 5 and 7 inches) were used to access the effect of phantom size on image noise. The smallest available field of view (25×25 cm) was used for all imaging. Given the 512×512 matrix size in CT images, scanned pixel dimension was < 0.5 mm. In order to test the effect of spatial resolution on image noise, pixels were grouped post-imaging to provide images with pixel dimensions ranging from 1 to 5 mm. MatLab (The MathWorks Inc. Natick, USA) was used for all image processing and analysis.
Table 1. Scan parameters used. The reference set is in bold.

| Scan parameter (units) | Values                  |
|------------------------|-------------------------|
| Tube voltage (kV)      | 80, 100, 120, **140**   |
| Tube current (mA)      | 100, 150, **200**, 250, 300, 380 |
| Slice scan time (s)    | 0.8, **1**, 2, 3, 4     |
| Slice thickness (mm)   | 1, **3**, 5, 7, 10      |
| Reconstruction algorithm | **Standard**, Soft, Lung, Detail, Bone, Edge |

3. Factors affecting image noise

Noise in CT images is primarily due to the quantum noise inherent in photon detection and electronic noise in the projection data. Electronic noise is relatively constant, however quantum noise is related, in theory, to the number of photons counted, $N$, by $1/\sqrt{N}$. $N$ depends on detector efficiency and the number of photons incident on the detector and hence on factors such as scan technique, phantom size and spatial resolution. In addition, when reconstructing images from projection data, algorithms employ filters that impact noise in the final image. The effects of these factors on image noise are evaluated in the following sections.

3.1. Scan technique (kV, mA, s)

Increasing tube voltage (kV), tube current (mA) and slice scan time (s) decrease image noise as shown in figure 1. mA and s improve image noise by $1/\sqrt{mAs}$ (see fits, figure 1) which, since $N$ is linearly related to mA and s, is predicted by theory [6].

The relationship of kV to image noise is more complex as it affects the production of photons in the x-ray tube, via radiative stopping power, and photon attenuation in the phantom, via linear attenuation coefficient. kV is measured to improve noise by $\sim (kV)^{1.3}$. The implication is that increasing kV is a more efficient means of improving image noise than increasing mA or s since load on the x-ray tube is given by: $kJ = kV \times mA \times s$. As such, maximizing kV should be top priority for scan technique.

3.2. Phantom size

CT image noise is shown to dramatically increase with phantom size, as shown in figure 2. This is a result of increased photon attenuation in the phantom. The results, fit to an exponential, show that the relationship is clearly supra-linear. As a result, CT gel dosimetry phantoms should be as small as possible for each application.
3.3. Spatial resolution

Increasing both slice thickness and pixel dimension decrease image noise, as shown in figure 3. This is a direct result of increased photon counting statistics. N increases linearly with slice thickness and our results confirm the theoretical $1/\sqrt{\text{slice thickness}}$ decrease in image noise [6]. The effect of pixel dimension on noise is measured to be greater than that of slice thickness and is described well by an exponential (figure 3). These results have valuable clinical implications: in cases where 0.5mm resolution is unnecessary, such as in validation of treatment planning calculations where spatial resolution is 1 or 2 mm, these results indicate that noise can be significantly improved (~ 30 – 65 %) by reducing measured spatial resolution to 1 or 2 mm.
3.4. Reconstruction algorithm

The effect of the different reconstruction algorithms available on GE scanners on image noise is shown in figure 4. The dramatic variation in results highlights the importance of choosing an appropriate reconstruction algorithm for CT gel dosimetry.

![Figure 4. The effect of the reconstruction algorithm on image noise. All algorithms are standards for GE CT scanners.](image)

4. Techniques to further reduce image noise

Beyond appropriate consideration of these factors, there are several additional means of reducing noise in CT polymer gel images. Image averaging is a highly effective technique: noise is reduced with increasing averages (NAX) by $1/\sqrt{NAX}$ as predicted by theory. Digital image filtering is also effective in reducing image noise while maintaining accurate spatial dose information. The Adaptive mean and the relatively new SUSAN filters are recommended [7].

5. Conclusions

CT image noise is a critical factor in improving dose resolution in CT gel dosimetry. Appropriate choice of scan technique, reconstruction algorithm, spatial resolution and phantom size as well as use of image averaging and digital image filtering can dramatically reduce noise in CT gel images. In terms of scan technique, maximizing tube voltage should be a priority. Tube current, slice scan time and the number of images averaged should also be high, however these parameters will be limited by x-ray tube heating and the effect on total imaging time. Spatial resolution dramatically affects image noise and in some situations using a reduced spatial resolution should be considered. Careful choice of reconstruction algorithm is also critical. Finally, small phantoms should be used for CT gel dosimetry whenever possible.
References

[1] Hilts M, Audet C, Duzenli C and Jirasek A 2000 Polymer gel dosimetry using x-ray computed tomography: a feasibility study Phys. Med. Biol. 45 2559–71

[2] Audet C, Hilts M, Jirasek A and Duzenli C 2002 CT gel dosimetry technique: comparison of a planned and measured 3D stereotactic dose volume J. Appl. Clin. Med. Phys. 3 110–8

[3] Trapp J V, Bäck S Å J, Lepage M, Michael G and Baldock C 2001 An experimental study of the dose response of polymer gel dosimeters imaged with x-ray computed tomography Phys. Med.Biol. 46 2939–51

[4] Trapp J V, Michael G and Baldock C 2001 Theoretical considerations of scan parameters appropriate for CT imaging of polymer gel dosimeters Proc. 2nd Int. Conf. on Radiotherapy Gel Dosimetry (Brisbane, Australia) ed C Baldock and Y De Deene pp 184–6

[5] Hsieh J 2003 Computed Tomography: Principles, Design, Artifacts and Recent Advances (Bellingham: SPIE Press)

[6] Brooks R A and Di Chiro G 1976 Statistical limitations in x-ray reconstructive tomography Med.Phys. 3 237–40

[7] Hilts M and Duzenli C 2004 Image filtering for improved dose resolution in CT polymer gel dosimetry Med. Phys. 31 39–49