X-ray computed tomography imaging of polymer gel dosimeters

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1. Introduction
The use of x-ray computed tomography (CT) for the imaging of irradiated polymer gels was first introduced at the 1st international conference on radiotherapy gel dosimetry, DOSGEL99, and in a subsequent paper [1,2]. These works showed dose dependent contrast in CT images of irradiated polyacrylamide (PAG) gel, quantified a CT dose response for PAG gel and thereby established the potential of CT as an alternative to MRI and optical CT for gel read-out. Figure 1 shows an early example of CT contrast in a PAG gel irradiated with four photon beams [1]. CT read-out is an exciting option for gel dosimetry due to the accessibility of CT in clinical radiation therapy environments in the form of CT simulators used for treatment planning. This practical attraction combined with the dosimetric promise shown by the initial feasibility studies has led to increased research into x-ray CT read-out of polymer gel dosimeters. This paper aims to provide a review of past and current literature in x-ray CT gel dosimetry and in doing so to summarize the state of knowledge in the field. Fundamental x-ray CT properties of polymer gel, dose response characteristics, CT imaging considerations, image filtering for noise reduction and applications are discussed.

Figure 1. A CT image of irradiated polymer gel showing dose dependent contrast. This PAG gel was irradiated with four photon beams: Gy as shown in figure (2).
2. Fundamental x-ray CT properties of polymer gel

The following describes some of the theory and experimental studies that have investigated fundamental gel properties resulting in contrast in CT images of irradiated polymer gel. As introduction, the relationship between CT contrast and density is summarized. This is followed by a summary of experimental investigations on x-ray attenuation and density in polymer gels. Finally, a discussion on the effects of gel composition on the density change in irradiated polymer gel is provided.

2.1. CT contrast and density

Pixel intensity in CT images is expressed as CT numbers ($N_{CT}$), typically in Hounsfield units (H). $N_{CT}$ are measures of the linear attenuation coefficient of the sample ($\mu$) relative to that of water ($\mu_w$):

$$N_{CT} = 1000 \times \frac{\mu - \mu_w}{\mu_w}.$$  \hspace{1cm} (1)

The $N_{CT}$ of polymer gel changes ($\Delta N_{CT}$) when irradiated. As discussed by Trapp et al \cite{3}, density is, in theory, the only gel parameter affecting $\mu$ (and therefore $N_{CT}$) expected to change with irradiation. As a result, one can show that irradiated gel $\Delta N_{CT}$ is directly proportional to a change in gel density ($\Delta \rho_{gel}$):

$$\Delta \rho_{gel} = K \Delta N_{CT}$$  \hspace{1cm} (2)

where $K$, a function of un-irradiated gel density and $N_{CT}$, is a constant. For PAG gel, $K \approx 1$ and $\Delta N_{CT}$ in H is numerically equivalent to gel density change in kg m$^{-3}$ \cite{4}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{PAG density as a function of dose (a) and PAG linear attenuation coefficient ($\mu$) as a function of density (b). The linear relationship between $\mu$ and density confirms that CT contrast in images of irradiated PAG is due to changes in gel density \cite{3}.}
\end{figure}
2.2. X-ray attenuation and density in irradiated polymer gel
Direct measurements of the change in PAG linear attenuation coefficient ($\mu$) with dose were made by Trapp et al independent of CT imaging [3]. Their results proved that a change in $\mu$ with dose accounts for the observed $\Delta N_{CT}$ in CT images of irradiated PAG. Trapp et al also measured the change in PAG density with dose (figure 2a) using volumetric flasks. A comparison with the $\mu$ results indicated that the change in PAG $\mu$ is linearly related to the change in density (figure 2b) and thereby confirmed the theory (as described above) that CT contrast in irradiated PAG is the result of a density change in the gel [3]. The change in gel density with dose was also measured by Mather et al for PAG as well as the normoxic methacrylic acid based MAGIC gel [5]. Again, high precision gas volumetric chambers were used. Their results indicate a smaller change in density with dose for the MAGIC than the PAG gels.

Since no mass is added to polymer gels through irradiation, the observed change in density must be due to either a change in the distribution of mass within the system or to a change in gel volume. In the second case, a volumetric decrease would be required to account for the increase in gel density with dose. This raises concerns about potential loss of spatial integrity in polymer gels due to radiation induced shrinkage. This was addressed by Trapp et al in a work presented at DOSGEL2001 [6] where they provided a rough calculation to show that four times the currently observed PAG density change is allowable before spatial distortions exceed 2 mm, the spatial resolution limit set by the International Commission on Radiation Units and Measurements (ICRU).

2.3. Gel composition and density change
A model has been developed to aid in understanding the density change observed in irradiated polymer gel [4]. The model describes the density change as a function of the amount of polymer formed and an intrinsic density change that occurs when monomer is converted to polymer. This model, combined with experimental investigations of PAG gel performed using CT and Raman spectroscopy, revealed two properties of PAG density change. The first is that the intrinsic density change occurring per weight fraction monomer converted to polymer depends on the fraction of monomer that is the bis-acrylamide crosslinker (%C). Since %C affects the structure of the formed polymer, it is likely that PAG density change depends on this polymer structure. The second property is that the total PAG density change is linearly related to the total fraction of monomer in the system (%T). This highlights increasing %T as a potential method for improving contrast in CT gel images.

3. Dose response characteristics
The first polymer gel CT dose response was presented at DOSGEL99 for a standard PAG gel formulation (6%T, 50%C) [2]. Since this time, the CT dose response characteristics of PAG gel have been extensively studied. Information is now available on dose response characteristics such as the effect of composition on sensitivity, dose range, reproducibility, temperature effects etc. More recent investigations have begun exploring the CT dose response of normoxic gels, however, at this time knowledge is limited largely to dose response sensitivity and dose range for standard gel compositions. The following summarizes the current understanding of dose response characteristics for PAG and normoxic gel systems. Dose sensitivity, dose range and dose resolution results are summarized in Table 1.

3.1. Sensitivity and dose range
The dose response for a standard PAG (6%T, 50%C) is mono-exponential with a saturation dose of ~ 25Gy. The sensitivity of the “quasi-linear” low dose region (0 to 8 or 10 Gy) ranges from 0.71 ± 0.02 to 0.86 ± 0.04 H Gy$^{-1}$, depending on the research group [1,4,7]. Note that results are very reproducible for a given research group (see below) and observed differences between research groups are likely due to slight variations in manufacturing techniques. Trapp et al found an increase in the CT dose response with PAG %T and a slight decrease in sensitivity with gelatin concentration [7]. They also found that use of agarose in place of gelatin produced a significantly more sensitive, although less
predictable, dose response. Hilts et al determined that the increase in gel dose response sensitivity with %T is linear such that doubling %T will double sensitivity (figure 3a) [4]. In this same work, PAG %C was found to have significant effect on CT dose response with mid-range %C gels exhibiting sensitive, exponential responses and low and high %C gels exhibiting weaker, highly linear responses (figure 3b). The weaker responses also exhibited large dose ranges [8]. In particular, a 100% C PAG exhibits a relatively linear dose response out to at least 100 Gy [9].

The CT dose response of three normoxic gels have also been studied: MAGIC, MAGAT and PAGAT (or nPAG) gels. MAGIC gel, the first normoxic dosimeter gel, is based on the polymerization of methacrylic acid in gelatin infused with copper (II) sulphate and uses ascorbic acid as antioxidant [10]. MAGAT uses the same methacrylic acid monomer but employs tetrakis (hydroxymethyl) phosphonium chloride (THPC) as antioxidant [11]. PAGAT (or nPAG) is a normoxic version of standard PAG gel (6%T, 50%C) again with THPC as antioxidant [11]. All three gels have mono-exponential CT dose responses with quasi-linear regions at lower doses. Hill et al showed that MAGIC gel exhibits a CT dose response significantly less sensitive than traditional PAG

**Figure 3.** (a) PAG sensitivity, density change per unit dose, increases linearly with %T. (b) PAG density change per unit dose is also affected by gel %C where low and high %C gels show less sensitive but more linear dose responses than mid-range %C gels [4].

**Figure 4.** (a) CT dose response of MAGIC gel. Dose sensitivity is lower for MAGIC than PAG gel. However the dose range, including “quasi-linear” region, is very large [12].
gel, but with a larger dose range (figure 4) [12]. They indicated a linear response from 0 to 60 Gy which may prove very promising for relative dosimetry. The MAGAT gel has a CT dose response similar to traditional PAG gel both in terms of sensitivity and dose range [11]. In contrast, PAGAT gels exhibit a lowered dose response than traditional anoxic PAG gel. This was illustrated in works by Brindha et al and Jirasek et al which find very similar dose response sensitivities: $0.34 \pm 0.01 \text{ H Gy}^{-1}$ and $0.36 \pm 0.04 \text{ H Gy}^{-1}$ over linear regions of 0 to 10 and 16 Gy, respectively [13,14]. Venning et al have shown a more sensitive dose response for PAGAT [15]. The reason for this discrepancy is not clear. In their recent work Jirasek et al also examined the variation in PAGAT response with THPC concentration and determined 4.625 mM to provide maximum sensitivity [14].

Table 1. CT dose response data for studied polymer gel dosimeters.

| Polymer gel*          | Sensitivity (HGy$^{-1}$) | Linear $D_{\text{max}}$ (Gy) | Reported dose resolution (Gy)$^\dagger$ | Calc. relative dose resolution (%)$^\ddagger$ | Reference |
|-----------------------|--------------------------|-------------------------------|----------------------------------------|-----------------------------------------------|-----------|
| PAG                   | 0.86±0.04                | 8                             | 10.0                                   | 1                                             | 1         |
|                       | 0.71±0.02                | 10                            | 1.0                                    | 12.5                                          | 7         |
|                       | 0.83±0.03                | 8                             | 10.2                                   | 8                                             | 8         |
| PAG (12%T)            | 1.43±0.05                | 10                            | 1.1                                    | 4.8                                           | 7         |
| PAG (agarose)         | 1.2±0.1                  | 8                             | 2.4                                    | 7.0                                           | 7         |
| PAG (60°C)            | 0.226±0.006              | 20                            | 15.0                                   | 8                                             | 8         |
| PAG (70°C)            | 0.241±0.005              | 20                            | 14.1                                   | 8                                             | 8         |
| PAG (100%C,3%T)       | 0.039±0.002              | >100                          | 17.5                                   | 8                                             | 8         |
| PAGAT (or nPAG)       | 0.31±0.03                | 15                            | 14.6                                   | 11                                            | 11        |
|                       | 0.70±0.03                | ---                           | ---                                    | ---                                           | ---       |
|                       | 0.36±0.04                | 16                            | 11.8                                   | 14                                            | 14        |
| MAGIC                 | 0.85±0.08                | 10                            | 7.9                                    | 11                                            | 11        |
|                       | 0.38±0.07                | 60                            | 3.0                                    | 12                                            | 12        |

*All gel formulations are standard (6%T, 50%C- where applicable) except for parameters in parentheses.

$^\dagger$Dose resolution (absolute, Gy), 95% confidence, from Hill et al and Trapp et al [7,12].

$^\ddagger$Relative (%) dose resolution, 95% confidence, calculated using uncertainty in $N_{\text{CT}} = 0.3$ H for all gels. Actual dose resolution may vary depending on the image noise in a particular situation.

3.2. Dose resolution

Dose resolution, or minimum detectable difference in dose, is one of the most important features of a dosimeter. In CT gel dosimetry, the most significant factors affecting dose resolution are CT dose response sensitivity ($\frac{\Delta D}{\Delta N_{\text{CT}}}$) and the level of noise in the CT images ($\sigma_{N_{\text{CT}}}$) [16]. It is difficult to compare CT dose resolutions for different gel dosimeters since (as discussed further below) choice of imaging protocol will greatly affect image noise [17]. In a recent work Hill et al compare dose resolutions reported in the literature for various CT gel dosimeters (see Table 1) [12]. However they do not quote the imaging protocols used, making it difficult to assess whether observed differences are inherent in the gel systems or due to variations in imaging technique. In general we can ascertain that current CT gel dosimetry systems have dose resolutions (95% confidence) of $\sim 1 - 2$ Gy.

Focusing on the linear region of gel dose response, for which sensitivity is typically quoted, it makes sense to speak of relative or percentage dose resolution. This is because a primary advantage of a linear dose response is that the gel can be used as a relative dosimeter without requiring a calibration gel. Based on a definition by Gustavsson et al for MRI gel dosimetry [18], percentage dose resolution in CT gel dosimetry is given by:

$$D_{\Delta, \%} = \left( \frac{\Delta D}{\Delta N_{\text{CT}}} \right) \sigma_{N_{\text{CT}}} \times 100\%.$$  \hspace{1cm} (3)

$D_{\text{max}}$ is the maximum dose in the gel irradiation. As such, percentage dose resolution is maximized by irradiating the gel over its full linear dose range [9]. This equation gives dose resolution with one standard deviation (67% confidence level). For a 95% confidence level this result must be multiplied...
by 2.77. In an attempt to compare dose resolutions across CT gel dosimeters, percentage dose resolution, at a 95% confidence level, has been calculated from the available data using the same value of image noise for all gels (0.3 H) and assuming in each case the gels were irradiated over their full linear dose range. Results are given in Table 1. Note that while this allows the relative performance of the various dosimeters to be compared (independent of CT imaging technique) these values represent approximate dose resolutions and actual values may be better or worse depending on the actual level of image noise. It can be seen that even with its reduced sensitivity, MAGIC gel is promising for relative dosimetry due to its extended linear dose range. The MAGAT gel also holds promise showing a comparable sensitivity to PAG but a slightly larger linear dose range. The PAGAT gel performs worse than traditional PAG due to its low sensitivity. It is important to note however that dose resolution alone does not define an optimum gel dosimeter. As an example, although the 12%T PAG has a promising relative dose resolution, this gel is very difficult to manufacture and is impractical for routine use. Several other factors (e.g. stability, temperature dependence etc.) must be considered before selecting a dosimeter gel appropriate for clinical use and many of the gels discussed above have not yet been tested in these areas.

3.3. Reproducibility
By all accounts the reproducibility of PAG CT dose response is excellent. The initial feasibility study showed that dose response sensitivity is independent of the time of CT imaging [1]. The intra-batch reproducibility (9 vials from a single batch of PAG were irradiated to 8 Gy) was recently shown to be 0.1 H [8]. Furthermore, the inter-batch reproducibility is remarkable. Figure 5 shows dose responses measured for 4 independent batches of PAG gel over a period of several weeks [9]. This excellent reproducibility is not arduous to achieve and represents an advantage of CT read-out over other methods such as MRI. The CT dose response reproducibility of PAGAT normoxic gel has also recently been tested and was shown to be comparable to traditional PAG [14]. CT dose response reproducibility has not been reported for MAGAT and MAGIC gels.

3.4. Temperature dependence
The sensitivity of PAG CT dose response depends slightly on gel temperature during CT imaging. For standard PAG, a 0.5% change in sensitivity occurs per °C change in temperature [1]. This change

![Figure 5](image_url)

Figure 5. CT dose responses measured for four independent batches of PAG gel. Reproducibility is excellent: all dose responses agree well within error [9].
will not affect relative dose measurements, since linearity is preserved. For actual dose measurements, small changes in gel temperature, such as might occur throughout an imaging session, will not affect dose measurements. However use of a calibration gel imaged at one temperature (e.g. refrigerated) to predict dose in a gel imaged at a second temperature (e.g. room temperature) could cause errors in dose measurements. The effect of gel temperature on the CT dose response of other types of polymer gel has not been investigated.

3.5. Stability
PAG CT dose response is very stable with respect to imaging time. The slope of the linear portion of the dose response was found reproducible when the same gel was imaged over several days [1]. A similar investigation has been performed recently with the PAGAT gel and dose response found to be stable over time [14]. This study also investigated the effect of irradiation time post manufacture. Here gel response is found to be stable for several hours (up to 6) post manufacture. For longer times (e.g. 24 hours) oxygen contamination becomes apparent.

4. CT imaging considerations
Early work highlighted the effect of CT imaging technique on CT gel dosimetry [1]. X-ray tube heating was found to affect dose response and the value of image averaging and background subtraction in producing quality dose maps was demonstrated. Since this time, several works have discussed considerations for optimized CT imaging of gel dosimeters using commercial CT scanners [6,9,12,17] and these findings are summarized below. Complementary to this work with commercial systems, one group has investigated the possibility of building a bench-top micro-CT scanner for gel dosimetry [19]. This work offers the potential for high spatial resolution CT gel dosimetry but removes one of the largest advantages of CT read-out, the accessibility and speed of commercial CT systems.

4.1. Effect of imaging technique on dose response
The technique used for CT imaging does not affect the sensitivity of polymer gel CT dose response. The only imaging factor with this potential, tube voltage (since attenuation, \(\mu\), depends on beam energy), has been shown to have no effect for both PAG and MAGIC gels [8,12]. However, actual \(N_{CT}\) values for polymer gel can vary with x-ray tube temperature (1) and it is recommended to warm-up a CT scanner before using it for gel dosimetry.

4.2. Effect of imaging technique on image noise
CT imaging technique can have a dramatic effect on image noise and therefore, as described above, the achievable dose resolution of CT polymer gel systems. Several works have discussed the relationships between the parameters used to CT image polymer gel and the resulting image noise [6,9,12,17]. Reconstruction algorithm has the largest single effect on image noise. Inappropriate algorithm selection, e.g. “Edge” algorithm on a GE scanner, can produce images ~5 times noisier than standard algorithms [9]. Table 2 lists the quantitative effects on image noise of selectable imaging parameters (kV, mA, slice scan time, and slice thickness), number of image averages (NAX) and pixel dimension as achieved via binning pixels post-imaging [9]. In summary, increasing kV, mAs, slice thickness, NAX and pixel dimension (post-processing) all serve to reduce image noise. Of these parameters, kV has the largest effect on image noise. Field of view (FOV) is another parameter
Table 2. Factors affecting CT image noise.

| Factor affecting image noise (symbol) | Relationship to image noise ($\sigma_{CT}$) |
|--------------------------------------|--------------------------------------------|
| Phantom diameter ($d$)               | $\sigma_{CT} \propto e^d$                  |
| Tube voltage (kV)                    | $\sigma_{CT} \propto (kV)^{-1.4}$         |
| Tube current (mA)                    | $\sigma_{CT} \propto (mA)^{-0.5}$         |
| Slice scan time (s)                  | $\sigma_{CT} \propto s^{-0.5}$            |
| Number of averages (NAX)             | $\sigma_{CT} \propto (NAX)^{-0.5}$        |
| Pixel dimension ($w$)                | $\sigma_{CT} \propto e^{w (or w^{-0.65})}$ |
| Slice thickness ($h$)                | $\sigma_{CT} \propto h^{-0.5}$            |

selectable on many CT scanners and increasing FOV is found to increase image noise [12]. On a practical note, since CT imaging parameters affect image noise independently of one another, the noise level resulting from any imaging protocol can be deduced from a single noise measurement (given known imaging parameters) through application of the relationships given in Table 2.

4.3. Protocols for gel imaging

In selecting a protocol for CT imaging polymer gel one must consider requirements for dose resolution (and therefore image noise), imaging time and spatial resolution. The difficulty lies in the conflict between achieving low noise (high CT scanning technique, large slice thickness and pixel size) and achieving both high spatial resolution (thin slices and small pixel size) and short imaging times (fewer slices imaged, low scan technique and therefore reduced load on the x-ray tube). Compromise will always be required and the “optimum” imaging protocol will depend on the particular application. However, a few general recommendations can be made:

- Use a standard or low noise reconstruction algorithm.
- Maximize kV before increasing mA, s or NAX. This is because kV, mAs and NAX all affect load on the x-ray tube equally, but kV has the greatest affect on image noise.
- Maximize slice thickness and use a smooth reconstruction algorithm when imaging uniform dose calibration vials as spatial resolution is not important.

Figure 6. Evidence that background subtraction produces highly uniform CT images. Mean pixel values were measured in 36 distinct regions of a water filled phantom after performing background subtraction for artefact removal [9].
Aside from selection of appropriate scan parameters, a background subtraction procedure is recommended to remove artefacts from the images. This procedure was introduced with the feasibility of CT for gel read-out [1] and has been used with continued success since, in various forms, by all groups performing CT gel dosimetry. Figure 6 demonstrates the excellent uniformity in CT images after background subtraction is performed [9]. The procedure involves subtracting a background image of water or an unirradiated gel from the images of the gel of interest. For successful artefact removal the artefacts in both images must be the same. This requires use of the same container, identical imaging position and materials of similar density for both images. If a background gel is used (in lieu of water), the ratio of water to gelling agent should be equivalent to the irradiated gel as this is the greatest factor determining gel density. The monomers can be eliminated from the background gel recipe.

4.4. Phantom design
Phantom diameter affects image noise (see Table 2) so phantoms should be designed as small as possible for a given application [9]. In addition, high density containers (e.g. glass) can produce extreme artefacts that are difficult to remove by background subtraction. The same is true for high density rubber stoppers which should be removed during imaging [9].

Figure 7. Adaptive mean filtering (K = 3, n = 3) applied to a thyroid IMRT dose distribution with SNR = 20. Filtering is very successful at restoring the original noise-free image as seen in (a) the displayed isodose overlays, (b) profile through the spinal cord region, (c) Chi-distribution (a measure of dose difference and distance to agreement) and (d) dose area histogram [20].
5. Image filtering for noise reduction

CT gel dosimetry will always be a low contrast imaging technique. Noise reduction is critical to improving low contrast resolution, and hence, dose resolution. Although, as described above, optimized CT imaging technique can go a long way in reducing image noise, further noise reduction may prove necessary to achieve dose resolutions practical for clinical applications. Digital image filtering is being explored for this purpose and the following describes progress in this area.

5.1. Spatial, kernel or “mask” based filtering

In a work by Hilts and Duzenli a range of spatial, “kernel” based image filters were investigated for use in CT gel dosimetry [17]. The filters were applied to a stereotactic radiosurgery (SRS) dose distribution and were evaluated and compared based on their ability to 1) reduce image noise and 2) preserve the spatial distribution of dose. Two filters, the adaptive mean and SUSAN filters, performed strongly, providing ~ 50% reduction in image noise while producing very minimal distortion in spatial dose information. Recent work [20] has shown the adaptive mean filter to outperform the Susan filter for a wide variety of dose distributions and this is the recommended “kernel” type filtering technique. The power of adaptive mean filtering can be altered by varying kernel size (K) and the number of iterations (n). The optimum filtering strategy will depend on the dose distribution being filtered. Figure 7 shows the results of adaptive mean filtering (K = 3, n = 3) the dose distribution from a thyroid IMRT treatment with applied Gaussian noise (SNR = 20) [20]. Adaptive mean filtering does a remarkably good job at restoring the original, noise free image based on all clinically relevant comparison tools (isodose overlays, profiles, Chi-map and dose area histogram).

5.2. TPMEM filtering

A novel filtering technique based on a 2D two-point maximum entropy regularization method (TPMEM) has been developed and shows promise for noise reduction in CT gel dosimetry [21]. The method offers advantages over traditional, kernel based filtering approaches due to an enhanced flexibility in tuning the filter to balance the complementary requirements of noise reduction and maintaining image fidelity. Results for both synthetic dose distribution patterns and an actual irradiated polymer gel (SRS dose distribution) are very good. SNR enhancement factors > 15 are possible with minimal distortion of original image detail [21].

6. Applications

Research in CT polymer gel dosimetry has thus far focused largely on the fundamental development of the technique, and, as such, studies illustrating applications are rather scarce. The following describes the few applications present in the literature at this time. Future work is required in this area.

6.1. Radiation therapy

To illustrate the clinical potential of CT gel dosimetry, the initial feasibility work was followed up with an application to 3D dose measurement of a stereotactic radiosurgery (SRS) treatment [22]. This work showed (figure 8) that the technique could correctly localize the high dose region delivered by SRS, but lacked sufficient sensitivity to accurately define low doses. In another application, the high spatial resolution capabilities of the technique were highlighted by measuring the PDD from a clinical proton beam [23]. The reduced response of polymer gel to high LET radiation was also confirmed by this work.

6.2. CT scanner quality assurance

Drawing from the concept of CT gel dosimetry, recent work has investigated the application of polymer gels for measuring the dose delivered by CT scanners. Hill et al show that irradiating an active MAGIC gel with a high technique CT scanning protocol (e.g. 400 mAs, 50 image averages) produces gel polymerization measurable with MRI readout [12]. This shows a potential role for
polymer gel dosimetry in CT scanner quality assurance, for example in the simultaneous measurement of CT dose and scanner slice profile. This work is complementary to investigations of CT read-out for gel dosimetry since it shows that dose from CT imaging has the potential to affect irradiated gels if not inert when imaged. Recent experiments by Jirasek et al, reported elsewhere in these proceedings, show the response of PAGAT gel to kV irradiation to be less than to MV irradiation and indicate that active nPAG gels will not be adversely affected by CT read-out when typical gel imaging protocols are used.

7. Summary: Advantages and limitations
There are several advantages of using x-ray CT for gel read-out. Many of these are practical advantages which benefit clinical implementation. Perhaps the most significant is the widespread accessibility of CT scanners to radiation therapy departments in the form of CT simulators for treatment planning. In addition, CT scanners are fast and easy to operate and both physicists and radiation therapists in cancer hospitals will frequently already be experienced operators thereby reducing the learning curve associated with implementation. In terms of dosimeter quality, CT read-out can offer images with small voxel size, a robust and stable dose response with low dependence on imaging temperature and a low level of image artefacts which can typically be removed by background subtraction.

There is however one significant disadvantage of current CT gel dosimetry systems: low dose response sensitivity. Recent work is showing this to be particularly true for normoxic MAGIC and PAGAT gels. However, when used for relative dosimetry an increased linear dose range may in some cases compensate for the low dose response. An additional potential disadvantage is the delivery of radiation to the gel through the read-out process. However, recent work presented at this meeting (DOSGEL 2006) indicates that gels will be unaffected by typical gel CT imaging protocols.

In conclusion, x-ray CT gel dosimetry is a promising option for practical clinical implementation of gel dosimetry. Future work is required to improve sensitivity and develop applications.

![Figure 8](image.png)

Figure 8. Application of CT PAG dosimetry to 3D dose measurement of a SRS treatment. Axial, sagittal and coronal planes are shown. Isodose lines are treatment planning calculations (22).
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