Characterization of a normoxic polyacrylamide gel using MRI and optical CT

Malcolm Heard\textsuperscript{1}, Geoffrey Ibbott\textsuperscript{1}, David Followill\textsuperscript{1}, R. Allen White\textsuperscript{2}, Edward Jackson\textsuperscript{3}, Mohammad Salehpour\textsuperscript{1}

\textsuperscript{1}Radiation Physics, University of Texas M.D. Anderson Cancer Center, 1515 Holcombe Blvd, Houston, Texas 77030
\textsuperscript{2}Biostatics and Applied Math, University of Texas M.D. Anderson Cancer Center, 1515 Holcombe Blvd, Houston, Texas 77030
\textsuperscript{3}Imaging Physics, University of Texas M.D. Anderson Cancer Center, 1515 Holcombe Blvd, Houston, Texas 77030

mheard@mdanderson.org

1. Introduction
The field of gel dosimetry grew out of the observation that changes in certain gel formulations in response to radiation could be demonstrated through magnetic resonance imaging (MRI) \cite{1}. MRI continues to be the most widely used method of evaluating gels. The major disadvantages of MRI are the difficulties experienced in gaining access to an imager and the expertise necessary to achieve the accurate quantitative imaging required for 3D dosimetry. Since 1993, the availability of MR scanners has significantly increased. Presently, several radiotherapy departments are investigating the use of MRI for treatment planning \cite{2}. The increased availability of MRI should increase the access for gel imaging. The 3D dosimetry community, through DOSGEL meetings and the discussion forum, has helped to inform users on the optimal techniques for the imaging of polymer gels with MRI.

Gore et al. \cite{3} developed an optical CT system to provide an alternative to MRI for imaging polymer gels. The idea was to provide a method for imaging the gels that would be easily accessible and low-cost. A major limitation of optical imaging has been the amount of time required to perform the imaging. The development of new optical scanners and upgrades to the designs of already existing models has significantly reduced the imaging time.

Both imaging modalities have been used in studies that characterized polymer gel formulations and in studies demonstrating the ability of polymer gels to be used as a clinical tool. Despite the growth in both areas, few studies have been done using both imaging modalities. The purpose of this study was to characterize a polymer gel dosimeters using both MRI and optical CT and to compare the characteristics of the two imaging modalities.

2. Materials and Methods
For this study, a PAGAT gel containing 4.5\% N,N’–methylene-bis-acrylamide (bis), 4.5\% acrylamide (AA), 5\% gelatine, 5 mM tetrakis (hydroxymethyl) phosphonium chloride (THPC), 0.01 mM hydroquinone (HQ) and 86\% H\textsubscript{2}O was manufactured according to procedures developed by Venning et al. \cite{4}. A slight change was made to the manufacturing procedure as the gels were not made in normal atmospheric conditions. Instead, all gels were made in an AtmosBag\textsuperscript{TM} (Sigma-Aldrich,
Milwaukee, WI) in a nitrogen environment. The gels were mixed and poured in PET jars, 5 cm in diameter and 5 cm in height, and sealed. The gels were immediately placed in zip-top bags and sealed before removal to normal atmospheric conditions. This change to the manufacturing procedure prevented oxygen contamination through the polypropylene cap of the PET jar. The gels were stored for 24 hours before irradiation.

Four different batches of PAGAT gel were made for this study. Three batches were used to determine the dose response, inter-batch reproducibility, and dose resolution. Each dosimeter was placed in a water tank and irradiated using a 20 x 20 cm$^2$ pair of parallel-opposed 6 MV beams. Each batch of dosimeters was irradiated to doses from 1 Gy to 10 Gy. The fourth batch of gel was used to evaluate the spatial stability of the gel and the intra-batch reproducibility. Each gel was placed in a water tank and irradiated using a half-blocked 5 x 10 cm$^2$ field from a 6 MV accelerator to create a steep dose gradient. Three dosimeters were irradiated to 2 Gy at a depth of 5 cm, three dosimeters were irradiated to 5 Gy at a depth of 5 cm, and three dosimeters were irradiated to 8.25 Gy at a depth of 5 cm. Radiochromic film was also irradiated using the same beam configuration in a phantom of water-equivalent plastic. Dose levels of 2 Gy, 5 Gy, and 8.25 Gy were delivered to the film at a depth of 5 cm.

Immediately following irradiation, all gels were placed in the MRI scanning room to equilibrate to room temperature overnight. Imaging was performed 24 hours after irradiation using a Bruker 4.7 T research MRI scanner. $T_2$ weighted imaging was performed using 64 equidistant spin-echoes with a TE of 9 ms, TR of 6500 ms, slice thickness of 2 mm, matrix size of 64 x 64, FOV of 80 mm in both the frequency and phase encoding directions with one acquisition. The base images were transferred to a personal computer and fitted to a mono-exponential decay curve using MATLAB™ (The Math Works, Inc.). Additional software was written in MATLAB™ to compute $R_2$ maps and perform additional analysis.

Immediately after MR imaging of the gels, they were transferred to the optical CT room. The fast-scanning platform of the OCT-OPUS™ laser CT scanner (MGS Research Inc., Madison, CT) was used. An in-plane resolution of 1 x 1 mm$^2$ was used.

3. Results and Discussion

The dose response of three different batches of PAGAT gel is displayed in Figures 1 and 3. The dose response using optical CT could only be determined up to 7 Gy as dosimeters irradiated to higher doses were too optically dense to be imaged. The response of the dosimeters at each dose level was compared to determine the inter-batch reproducibility. The differences in $R_2$ were as large as 4.6% at 5 Gy and the differences in net OD were as large as 20% at 7 Gy. Figures 2 and 4 show the dose resolution using a 95% confidence limit. The best dose resolution was achieved when optical CT was used because of the large $\Delta$ net OD/$\Delta$ Dose.

Figures 5-8 are profiles from gels irradiated with a half-blocked field. The profiles were normalized at 15 mm from the central axis. Figures 5 and 6 show excellent agreement between film and PAGAT gel. No dose overshoots were observed near the steep dose gradient. Figure 7 and 8 show disagreement between film and gel in the low dose region. These differences are attributed to the performance of the optical CT system when measuring low OD values. The uncertainty in the determination of the OD can be as large 5.5%. In addition, the gels with low OD values are affected by a ring artifact that resulted in the “wave” structure seen in the 2 Gy profile. Figure 9 displays the maximum percent difference between dosimeters within the same batch irradiated to the same dose. Difference as large as 3.7% were observed for gels imaged with optical CT and differences as large as 7.3% were observed in gels imaged with MRI. The data suggest that these dosimeters should be used as relative dosimeters since there can be significant differences in the response of gels within the same batch.
Figure 1. Dose response of 3 batches of PAGAT gel imaged with MRI. Error bars represent one standard deviation.

Figure 2. Dose resolution of 3 batches of PAGAT gel imaged with MRI.

Figure 3. Dose response of 3 batches of PAGAT gel imaged with optical CT. Error bars represent one standard deviation.

Figure 4. Dose resolution of 3 batches of PAGAT gel imaged with optical CT.

Figure 5. Profile through gels irradiated to 8.25 Gy with a half-blocked field and imaged with MRI.

Figure 6. Profile through gels irradiated to 2 Gy with a half-blocked field and imaged with MRI.
Figure 7. Profile through gels irradiated to 8.25 Gy with a half-blocked field and imaged with optical CT.

Figure 8. Profile through gels irradiated to 2 Gy with a half-blocked field and imaged with optical CT.

Figure 9. Intra-batch reproducibility of PAGAT gel.

References
[1] Maryanski, M. J., Gore, J. C., Kennan, R. P., and Schulz, R. J., 1993. NMR relaxation enhancement in gels polymerized and cross-linked by ionizing radiation: a new approach to 3D dosimetry by MRI. Magnetic Resonance Imaging 11, 253-258.

[2] Chen, L., Price Jr., R. A., Nguyen, T. B., Wang, L., Li, J. S., Qin, L., Ding, M., Palacio, E., Ma, C. M., and Pollack, A., 2004. Dosimetric evaluation of MRI-based treatment planning for prostate cancer. Phys. Med. Biol. 49, 5157–5170.

[3] Gore, J. C., Ranade, M., Maryanski, M. J., and Schulz, R. J., 1996. Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: I. Development of an optical scanner. Phys. Med. Biol. 41, 2695-2704.

[4] Venning, A. J., Hill, B., Brindha, S., Healey, B. J., and Baldock, C., 2005. Investigation of the PAGAT polymer gel dosimeter using magnetic resonance imaging. Phys. Med. Biol. 50, 3875-3888.