Abstract. With recent advances in magnetic resonance image-guided radiation therapy (MR-IGRT), Fricke gel dosimetry has demonstrated value for its ability to measure three-dimensional dose distributions in the presence of a strong magnetic field. This strong magnetic field causes hot and cold spots in dose distributions at the interfaces of lung and normal tissue due to a phenomenon known as the electron return effect (ERE). In this paper, we report the development of lung-equivalent gel dosimeters to better measure dose to lung tissue caused by the ERE. Small polystyrene beads of variable sizes were mixed into Fricke xylene orange gelatin (FXG) and ferrous oxide xylene orange (FOX) gels. Lung-equivalence was confirmed by measuring the average CT number of each gel. The effects of gel type, bead size, and voxel size on uniformity and signal intensity were investigated. The smallest beads (<1 mm) exhibited the best uniformity, with values comparable to conventional gel with 2 mm voxels. Signal intensity followed an inverse relationship with uniformity, but FXG low-density dosimeters generated enough signal to produce acceptable quality images. The spin-lattice relaxation rate (R1 = 1/T1) increased with dose, which enabled us to measure dose to both soft tissue and lung due to the ERE using a phantom simulating the soft tissue-lung interface.

1. Introduction
In recent years, a 1.5 T magnetic resonance imaging (MRI) system has been integrated with a 7 MV linear accelerator to produce an MR-image guided radiation therapy (MR-IGRT) system known as the MR-linac (Elekta AB, Stockholm, Sweden) [1-2]. MRI offers several advantages compared to conventional on-board imaging techniques for IGRT such as orthogonal x-ray planar imaging and computed tomography (CT). These advantages include superior soft tissue contrast, improved verification of patient setup, reduced ionizing radiation dose to the patient, and the ability to generate highly conformal treatment plans through adaptive replanning.

In the MR-linac, the strong magnetic field (B0-field) presents several dosimetric challenges due to the Lorentz forces acting on the secondary electrons. At interfaces between high- and low-density regions, a phenomenon known as the electron return effect (ERE) causes hot and cold spots in the dose distribution [3-4]. Secondary electrons entering a low-density region can be re-directed back toward the high-density region, causing more dose to be deposited in the denser tissue. The ERE is of particular concern in the thoracic region where there are interfaces between lung, airways, soft tissue, and bone.

As a result of the ERE and the highly conformal treatment plans that can be delivered on the MR-linac, there is a demand for a dosimetry system that can measure steep dose gradients in three dimensions. Conventional quality assurance (QA) tools can provide, at best, discrete point...
measurements in a pseudo-3D array [5]. Gel dosimetry has been used as an alternative QA method due to its ability to measure continuous volumetric dose distributions [6]. Fricke-based gels are particularly useful for the MR-linac because the radiation-induced oxidation of Fe$^{2+}$ to Fe$^{3+}$ and the corresponding change in spin-lattice relaxation rate ($R_1 = 1/T_1$) is linear with dose and can be measured using MRI [7-9].

Conventional gel formulations are water-equivalent, so they are optimized for measuring dose to soft tissue but not to lung tissue. Previous studies have explored the development of lung-equivalent gels using two different methods to reduce the density of the gel [10-15]. One technique involves beating the gel to a foam-like consistency before it sets, and the second involves mixing gel with small polystyrene beads to simulate air pockets. In this study, we used the latter method with two Fricke-type gels to optimize lung-equivalent gels for use with MR-IGRT systems.

Two concerns with the low-density gel dosimeters are the reduced MRI signal intensity and the heterogeneity caused by the presence of the polystyrene beads. Polystyrene generates no MR signal [16], so the total MR signal in the low-density gel is reduced compared to conventional gel. Further, the heterogeneous composition of the low-density gels may interfere with the resolution at which absorbed dose can be measured. This investigation was an effort to mitigate these issues by changing the sizes of the polystyrene beads and imaging voxels.

2. Materials and Methods

2.1. Gel Preparation

The two radiochromic gel formulations used in this study were Fricke xylenol orange gelatin (FXG) and ferrous oxide xylenol orange (FOX) [17-18]. FXG and FOX gels were formulated in-house using the following chemical components and concentrations: ~96% w/w deionized water, 4% w/w 300 bloom gelatin, 0.05 mM xylenol orange disodium salt, 50 mM sulfuric acid, and 1 mM ammonium iron(II) sulfate hexahydrate (FXG only) or 1 mM iron(II) oxide (FOX only). All chemicals were obtained from Sigma-Aldrich. For each batch, the gelatin was first mixed with water at 40˚C to ensure complete dissolution, then cooled to 25˚C prior to the addition of other components. The gels were refrigerated at 4˚C for about 24 hours as they solidified, then they were stored at room temperature for about 3 hours prior to irradiation.

Each lung-equivalent gel was created by adding the liquid gel formulation into a cylindrical container (5.5 cm diameter, 11.5 cm height) filled with expanded polystyrene foam beads. Each container was filled completely with polystyrene beads prior to the addition of gel to ensure uniform mixing. Four different sized polystyrene beads were used (<1 mm, 2-3 mm, 2-4 mm, and 6-10 mm), and the conventional gel with no polystyrene beads (referred to as “gel-only”) was used for comparison. Lung-equivalent dosimeters were created using both FXG and FOX.

2.2. CT Number and Spin-Lattice Relaxation ($T_1$) Characteristics

The average CT number (Hounsfield units (HU)) of each dosimeter was measured to determine lung tissue equivalence. The dosimeters were imaged using CT (Philips Brilliance Big Bore, 120 kVp, 300 mAs, 1×1×1 mm$^3$ voxel size).

Gels were irradiated with a uniform 20×20 cm$^2$ field on a pre-clinical MR-linac such that the dose at the center of each gel was approximately 31 Gy. $T_1$ maps were generated using fifteen inversion recovery images (MR-linac, Philips Turbo Spin Echo pulse sequence, TR/TE = 2500/20 ms, pixel size = 0.833×0.833 mm$^2$, slice thickness = 5 mm, number of signal averages (NSA) = 1, and inversion times ranging from 150–1400 ms). A pixel-wise $T_1$ calculation was performed using in-house software, and the average $T_1$ value of each gel was determined. Gels were imaged both pre- and immediately post-irradiation to avoid degradation of the dose map due to diffusion.
2.3. MR Signal Intensity and Uniformity
The gels were imaged with a T1-weighted spin echo (SE) pulse sequence (TR/TE = 500/20 ms, NSA = 1) with 1×1×1 mm³, 2×2×2 mm³, 3×3×3 mm³, and 5×5×5 mm³ voxel sizes (henceforth referred to as 1 mm, 2 mm, 3 mm, and 5 mm voxel sizes). Uniformity was calculated from these T1-weighted images using the Uniformity Normalized Absolute Average Deviation (UNAAD) method [19-20], which is a pixel-wise measurement of the difference in each signal intensity value from the average. This method defines uniformity U as

\[ U = 100 \left( 1 - \frac{1}{N} \sum_{i=1}^{N} |Y_i - \bar{Y}| \right) \]

where \( \bar{Y} \) is the average pixel value within a region of interest (ROI), each \( Y_i \) is the pixel value of a single pixel, and \( N \) is the number of pixels in the ROI. The higher the value, the more uniform the image (maximum value of 100).

2.4. Electron Return Effect
A heterogeneous phantom containing low-density gel surrounded by conventional gel was created to simulate the lung-soft tissue interface. The inner cylinder (5.5 cm diameter) contained FXG with 2-4 mm polystyrene beads. The outer cylinder (10 cm diameter) contained conventional FXG gel. The phantom was oriented in the MR-linac so that the axis of the cylinder was parallel to the \( B_0 \)-field and perpendicular to the radiation beam. A uniform 16×22 cm² half-blocked field (gantry 90°) was delivered to the phantom such that the absorbed dose to water at the center of the phantom was approximately 23 Gy. The phantom was imaged using an inversion recovery pulse sequence to produce a T1 map as described in section 2.2.

3. Results and Discussion

3.1. CT Number and Spin-Lattice Relaxation (T1) Characteristics
The CT numbers for the gel-only dosimeters were extremely close to that of water (0 HU) (Table 1). For each low-density dosimeter, CT numbers were comparable to those of lung tissue (~ -700 HU), which indicated lung tissue equivalence. FOX exhibited slightly lower CT numbers than FXG for each bead size. Standard deviations in CT number increased as bead size increased.

| Bead size | FXG CT # | T1 (pre) | T1 (post) | FOX CT # | T1 (pre) | T1 (post) |
|-----------|----------|----------|-----------|----------|----------|-----------|
| <1 mm     | -596 ± 23| 835 ± 10 | 578 ± 10  | -611 ± 31| 999 ± 14 | 710 ± 11  |
| 2-3 mm    | -603 ± 167| 839 ± 6 | 590 ± 12  | -655 ± 127| 1009 ± 10| 714 ± 12  |
| 2-4 mm    | -606 ± 228| 845 ± 7 | 592 ± 13  | -635 ± 184| 1014 ± 12| 722 ± 15  |
| 6-10 mm   | -595 ± 368| 822 ± 109| 584 ± 78  | -591 ± 354| 970 ± 190| 697 ± 126 |
| Gel-only  | 15 ± 5   | 848 ± 2 | 608 ± 8   | 13 ± 6   | 1026 ± 6 | 769 ± 14  |

For both types of gel and both pre- and post-irradiation, the gel-only dosimeter had a slightly higher T1 value than each of the low-density dosimeters (Table 1). Polystyrene is not MR-visible, so it was expected that the presence of polystyrene would lower the average T1 values compared to gel alone [16]. All gels showed a decrease in T1 when irradiated, and the T1 value of each low-density dosimeter decreased by roughly the same amount as the gel-only dosimeter for each type of gel. The standard deviations in T1 were substantially higher for the 6-10 mm bead gels than for smaller beads and gel-only, which may translate to greater uncertainty in measured dose in future studies.
3.2. MR Signal Intensity and Uniformity

MR signal intensity increased linearly with voxel size for all gels, but the slopes of the signal intensities varied based on gel type and composition (Figure 1a). For each type of gel, the MR signal intensities of the low-density dosimeters were lower than that of the corresponding gel-only dosimeter. This is because the addition of the polystyrene beads reduces the amount of gel per unit volume, and the polystyrene produced no visible MR signal.

All FXG dosimeters produced a higher signal than their FOX counterparts, with the FXG low-density gels and the FOX low-density gels forming two distinct clusters on the graph (Figure 1a). This clustering demonstrated that the bead size had minimal impact on the signal intensity of the low-density dosimeters. Interestingly, the FOX gel-only curve fell within the low-density FXG cluster; the addition of polystyrene beads to FXG reduced the signal intensities to levels comparable with the FOX conventional gel. Considering that conventional FOX gel has been used successfully in dosimetry studies before [17-18], the signal intensity of low-density FXG is sufficient to produce acceptable quality images for dose analysis.

In general, uniformity improved with smaller bead size and larger voxel size (Figures 1b and 2). The signal uniformity for gels with 6-10 mm beads did not increase with voxel size because the beads were larger than all the voxel sizes used for imaging. For the three smallest bead sizes, uniformity increased most sharply between 1 mm and 3 mm voxel sizes, but there was little change beyond 3 mm. The smallest beads (<1 mm) performed the best, with uniformity values of FXG <1 mm comparable to those of FXG and FOX conventional gels at 2 mm voxel sizes and above. There was no consistent trend between uniformity and gel type, which suggested that bead size was the primary factor affecting uniformity.

3.3. Electron Return Effect

A line profile was drawn through a cross-sectional slice of the dose distribution of the lung-soft tissue phantom (Figure 3). Within the low-density inner cylinder, dose generally decreased as the beam penetrated deeper into the phantom. Small fluctuations were observed that might have been reduced if a smaller bead size had been used. There was a region of enhanced dose just to the left of the inner cylinder and a region of reduced dose just to the right of the inner cylinder. The hot and cold spots were
offset slightly with respect to the direction of the beam due to the curved path of the electrons in the magnetic field. These results are qualitatively consistent with previous Monte Carlo calculations and 3D dosimetry measurements of the ERE for phantoms with similar geometries [3, 17, 21]. Future work relating R1 to absorbed dose for the low-density gel would be required to determine the absolute percent change in dose.

Figure 2. Signal uniformity of each dosimeter as a function of voxel size.

Previous phantom measurements of the ERE have used dosimeters composed of normal tissue-equivalent materials containing air cavities [17, 22], allowing only dose to normal tissue to be measured. Another study used a lung-equivalent material inside a cavity but used film and ion chambers to generate two-dimensional and point measurements, respectively [23]. Our phantom design allowed us to measure the volumetric dose distribution to both normal tissue and lung tissue, which presented a significant advantage for simulating clinically relevant scenarios.

Figure 3. a) Cross-sectional slice of the R1 map of the lung-soft tissue phantom and b) line profile.

4. Conclusion
We demonstrated that low-density, lung-equivalent dosimeters can be created by adding small polystyrene spheres to FXG and FOX radiochromic gels. All low-density gels had lung-equivalent CT numbers, regardless of bead size or gel type. The addition of polystyrene beads did reduce the MR signal
intensity compared to conventional gel, but FXG low-density gels produced signal intensities very similar to that of FOX conventional gel. Uniformity improved with smaller bead sizes and larger voxel sizes, with the FXG <1 mm bead dosimeters reaching the same uniformity levels as conventional gel with 2 mm voxels. Based on these results, the low-density formulation containing FXG with <1 mm beads will most likely produce the highest resolution dose maps in future work.

This study also demonstrated that irradiation caused the T1 values of the low-density gels to decrease by roughly the same amount as the T1 values of the corresponding conventional gels. Consequently, we were able to demonstrate that a volumetric dose distribution could be measured in a phantom containing both soft tissue- and lung-equivalent gels as a proof of concept. (Future studies would include calibrating the T1 values to absorbed dose for the low-density gels to extend our work to absolute dosimetry applications.) These results indicate that our low-density gel formulation can be used with conventional gel to measure the effects of the ERE on dose to lung and normal tissue.

5. References
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