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MRI-BASED PROSTATE BRACHYTHERAPY SEED LOCALIZATION

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Abstract

A magnetic resonance imaging (MRI) pulse sequence and a corresponding image processing algorithm to localize prostate brachytherapy seeds during or after therapy are presented. Inversion-Recovery with ON-resonant water suppression (IRON) is an MRI methodology that generates positive contrast in regions of magnetic field susceptibility, as created by prostate brachytherapy seeds. Phantoms comprising of several materials found in brachytherapy seeds were created to assess the usability of the IRON pulse sequence for imaging seeds. Resulting images show that seed materials are clearly visible with high contrast using IRON, agreeing with theoretical predictions. A seed localization algorithm to process IRON images demonstrates the potential of this imaging technique for seed localization and dosimetry.

Keywords

magnetic resonance imaging; positive contrast; prostate brachytherapy; seed localization; blob detection

1. INTRODUCTION

With nearly 200,000 incident cases per year, prostate cancer is the most commonly diagnosed cancer among men in the United States [1], emphasizing the need to improve current diagnostic and therapeutic methods. One treatment for low-risk prostate cancer is prostate brachytherapy, a procedure of inserting needles in precise locations of the prostate to implant small radioactive sources known as seeds. Brachytherapy is a highly effective treatment for localized prostate cancer, but successful operations are dependent on proper treatment planning and seed placement. One of the major current limitations of intraoperative treatment planning is the inability to localize the seeds in relation to the prostate [2]. This inability to localize individual seeds prevents real-time dosimetry and therefore leads to suboptimal prostate cancer treatment.

MRI is a promising modality for guiding brachytherapy, since it provides excellent substructure imaging of the prostate. Currently, many practitioners use transrectal ultrasound (TRUS) accompanied by X-ray to guide seed placement in the operating room. While TRUS is useful for prostate imaging, it is an inadequate modality for visualizing seeds and substructures such as tumors. X-ray displays seeds well but images the prostate poorly.

Since MRI can image both the prostate and the needles used during seed deployment, MRI-guided brachytherapy has been tested and validated in over 500 patients using the Signa SP 0.5T open-bore scanner [3] and is now progressing toward conventional closed-bore scanners through the aid of robotics [4,5].

Localizing seeds within MR images has been problematic because the seeds generally appear as diffuse, dark voids (see Fig. 1). Previous studies have assessed MR pulse sequences in imaging brachytherapy seeds [6,7]. However, recent developments in pulse sequences that image local changes in susceptibility provide a new opportunity to revisit this topic. In this paper, we provide an initial demonstration of the potential to image and localize brachytherapy seeds using the Inversion-Recovery With ON-Resonant Water Suppression (IRON) pulse sequence [8]. Our results demonstrate a clarity of seed visualization that is unprecedented. The potential for localization of seeds using non-invasive MRI has implications both for in-scanner delivery of seeds and for postoperative evaluation of implant dosimetry profiles.

2. MATERIALS AND METHODS

2.1. Inversion-Recovery With ON-Resonant Water Suppression

IRON is a versatile MRI methodology that enables positive contrast visualization in regions of magnetic field susceptibility [8]. It is based on the principle that a particle (e.g., a seed) with a magnetic susceptibility different than that of its surroundings (e.g., tissue) causes a disturbance to the static magnetic field of the MR scanner [9]. If a sphere of magnetic susceptibility χ and radius a is placed at the origin in a homogeneous static magnetic field of magnitude B_0 along direction z , the resulting field disturbance is described by the equation

$$\Delta B_z = \frac{\Delta\chi B_0 a^3}{3} \frac{2z^2 - x^2 - y^2}{(x^2 + y^2 + z^2)^{5/2}} \quad (1)$$

where $\Delta\chi = \chi - \chi_{\text{surroundings}}$. The total magnetic field disturbance can be characterized as a dipole with positive ΔB_z values along the axis of the magnetic field surrounded by negative ΔB_z values in the form of an annulus (see Fig. 2). Such a particle therefore causes an external frequency shift of

$$\Delta\omega_{\text{external}} = \gamma \Delta B_z \quad (2)$$

where γ is the gyromagnetic ratio of hydrogen. It is clear from (1) and (2) that the presence of the particle produces components in the MR frequency spectrum that are distinct from the Larmor frequency of $\omega_0 = \gamma B_0$ [see Fig. 3(a)].

IRON selects these off-resonant protons near the susceptibility generating particle by deliberately applying a spectrally selective on-resonant radio frequency (RF) saturation pulse with a limited bandwidth (BW_{Sat}) prior to the imaging part of the pulse sequence [see Fig. 3(b)]. This suppresses the on-resonant water protons of the background tissue but leaves the off-resonant protons near the particle unaffected. The area around the susceptibility-generating particle can thus be seen with positive contrast. Moreover, the size of the area with positive signal can be controlled by BW_{Sat} and the level of background suppression can be controlled by the flip angle, α_{Sat} .

2.2. Seed Localization

Once IRON images have been acquired, the brachytherapy seeds must be localized for dosimetry calculation. We thus developed a localization algorithm based on the blob detection technique of the Laplacian of a Gaussian (LoG) [10] to determine seed coordinates from the IRON volume.

In order to apply the LoG, the first step to our localization algorithm is to apply morphological preprocessing so each seed appears more blob-like. To do so, a morphological top hat by reconstruction is applied to the complemented volume, resulting in an image with only the blob-like centers of the dipoles. Next, the volume is filtered by a LoG to narrow down the seed locations. The minima to this resulting image can be thresholded to obtain a binary image volume, each region containing one or more seeds.

Once we have a binary image, each region is then analyzed to determine the number of seeds in the region and, ultimately, the seed locations. By this point in the algorithm, due to scaling issues, seeds are generally well localized in the XY plane but not so well in the Z direction. We thus determine the number of seeds in each region by analyzing the region volume statistics. Once each region's seed count is determined, the region is divided into equal subregions along the Z axis, where finally, the centroids of each subregion determine the seed coordinates.

2.3. Experiment

We built two MRI compatible phantoms to assess the potential of using IRON for prostate brachytherapy seed visualization and localization. Typical seed compositions were first researched to determine which materials should be included in the phantom. In general, seeds consist of radioactive agents such as iodine-125 or palladium-103. The outer cylindrical shell is often composed of titanium or stainless steel. Seeds also contain gold or silver spheres to serve as X-ray markers.

The first phantom is made of gelatin (Knox; Kraft Foods, Tarrytown, NY, USA) embedded with five layers of three “seeds” each, for a total of fifteen seeds. The “seeds” in each of the five layers are made of different seed-related materials (dimensions shown in Table 1), in particular, 99.95% pure nonradioactive palladium, 99.95% pure silver, titanium alloy Ti6Al, nonmagnetic stainless steel, and training seeds (TheraSeed; Theragenics Corporation, Buford, GA, USA). The training seeds, however, are not equivalent to actual seeds because they are not radioactive. The second phantom is also made of gelatin, but this time in a 61 nonradioactive palladium “seed” configuration inserted using an actual treatment plan.

MR imaging was carried out on a 3T Achieva MRI system (Philips Medical Systems). For the first phantom, the parameters for the on-resonant water suppression prepulse were $BW_{Sat} = 100$ Hz and $\alpha_{Sat} = 90^\circ$, determined and optimized for the first palladium layer. Imaging time was 3.7 minutes per layer. The parameters for the second phantom were $BW_{Sat} = 40$ Hz and $\alpha_{Sat} = 110^\circ$ with total imaging time of 15 minutes. Typical parameters for the three-dimensional segmented k-space gradient-echo (GRE) imaging sequence that followed the IRON prepulse were as follows: 3.9/1.5, 19 broadband on-resonant radiofrequency excitations per k-space segment with a constant 15° flip angle, 74 msec acquisition window, 140×112 mm field of view, partial echo, 642 Hz/pixel bandwidth, and 288×220 image matrix.

3. RESULTS

The resulting MR images of the first phantom are shown in Figs. 4 and 5. Table 2 shows volume magnetic susceptibilities [9] as well as summarized statistics.

The difference that the IRON prepulse makes in the appearance of the seeds is clearly evident in these figures. In Fig. 4, the cylinders appear as dark unclear voids. On the other hand, images with the IRON prepulse in Fig. 5 show strong positive contrast with a characteristic dipole shape. The background is also significantly darkened due to the suppression of on-resonant protons in the gelatin. Although this background suppression is inhomogeneous near the boundaries (red arrows in Fig. 5), this is expected behavior as susceptibility differences near the phantom borders also generate off-resonant protons.

The size and contrast of each material also generally correlate with $\Delta\chi$ (see Table 2), and therefore follows (1). Stainless steel seems to be an exception, since it appears smaller than palladium although theoretically it has a larger $\Delta\chi$. However, the actual $\Delta\chi$ of the stainless steel seeds in the phantom is uncertain and may truly be less than palladium. This is suggested not only by Fig. 5 and Table 2 but also by Fig. 4 taken prior to any IRON imaging.

This agreement with theory is further exemplified in the isosurface shown in Fig. 6. The shapes of the three palladium cylinders in Fig. 6(a) are clearly similar to the characteristic dipole shape shown for a sphere in Fig. 2(d). (1) suggests both positive and negative magnetic field distortions; however, IRON shows both distortions with positive contrast. Although simulations of a finite cylinder would be more suitable, the physics of such a magnetic field distortion is not easily described and was therefore not simulated. Nonetheless, the similarity of the phantom's short finite cylinders to the spherical model shows that IRON produces images as was expected through theory.

Finally, it may appear at first glance that it is not easy to localize the seeds because of the extended pattern that is characteristic of the IRON images. However, we developed the localization algorithm described in Sec. 2.2 and applied it to the more realistic 61 seed configuration of the second phantom as an initial demonstration to determine its feasibility.

Fig. 7 shows a slice through the simulated and actual IRON MRI volumes, while Fig. 8 shows steps along the process of the localization algorithm. In the simulation, 61 of 61 seeds were correctly localized with a mean localization error of 1.1643 mm (standard deviation 0.7412). Running time in MATLAB was 70 s for the $512 \times 512 \times 60$ double precision volume on a 2.33 GHz Intel Core 2 Duo CPU. In the IRON MRI case, 62 seeds were identified (1 false positive) with a mean localization difference of 2.5660 mm (standard deviation 1.6851) when compared to manual segmentation. Running time was longer at 123 s since the algorithm needed to be adjusted for the longer cylindrical seeds in the IRON volume as compared to the spheres in the simulation.

4. DISCUSSION

In all, this study shows the feasibility of using the IRON pulse sequence for seed localization in MRI. With palladium depicted very well in the phantom images, we expect actual palladium-103 seeds to be similarly well visualized through IRON imaging. Even iodine-125 seeds should be visible with IRON MRI as they often have titanium or stainless steel shells, both of which produce large signals. As signal strength can be adjusted with BW_{Sat} , this also leaves room for an adjustment in size should seeds of either type appear too large or too small.

The initial localization algorithm also shows that seeds imaged by IRON can be easily detected. Without IRON imaging, seed localization can be challenging for a human, much more so for a localization algorithm. With IRON imaging, however, simple localization algorithms can complete the task well.

In the future, more realistic phantom experiments need to be carried out in order to properly discern the appearance of brachytherapy seeds in a clinical setting. This involves replacing pure materials with more seed-like objects, while also increasing the density of seeds. Moreover, as air can result in positive contrast signals through IRON, air-prone organs near the prostate, such as the rectum or the urethra, must also be emulated to assess such an effect. Lastly, a clinical study with patients and actual seeds should also be conducted to make intraoperative seed localization and real-time dosimetry in MRI a reality.

In summary, this study presents exciting opportunities in MRI brachytherapy research. IRON has shown to be a promising methodology for imaging seeds, avoiding the disadvantages of conventional MR pulse sequences. With proper seed localization techniques, it consequently allows MRI to be more effective in guiding brachytherapy operations than TRUS or X-ray. Finally, as intraoperative seed localization and real-time dosimetry are a near possibility, prostate cancer patients can receive more optimized cancer treatment with IRON enhanced MRI-guided prostate brachytherapy.

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Fig. 1.
(a) Fast Spin Echo (FSE) image of the prostate. (b) Magnified view of the prostate area (white box) in (a). Red circles indicate three implanted seeds.

Fig. 2. Simulation of the magnetic field disturbance caused by a palladium sphere of radius 0.5 mm in water. (a) XY view. (b) XZ view. (c) YZ view. (d) Isosurface.

Fig. 3.
 (a) MR frequency spectrum without IRON prepulse. (b) MR frequency spectrum with IRON prepulse.

Fig. 4. GRE slice images of the five phantom materials without the IRON prepulse. (a) Palladium. (b) Silver. (c) Titanium. (d) Stainless steel. (e) Training seed (Theraseed).

Fig. 5. GRE slice images of the five phantom materials with the IRON prepulse. Red arrows show areas of inhomogeneous background suppression. (a) Palladium. (b) Silver. (c) Titanium. (d) Stainless steel. (e) Training seed (Theraseed).

Fig. 6. Isosurface of palladium layer using IRON imaging. Red arrows show areas of positive distortion shown with positive contrast; blue arrows show areas of negative distortion shown with positive contrast.

Fig. 7.

(a) Slice in the simulation volume of 61 seed phantom. (b) Slice in the MRI IRON volume of 61 seed phantom.

Fig. 8. Steps of localization algorithm on IRON volume. (a) Slice after morphological top hat by reconstruction. (b) Slice after LoG. (c) Slice after binarizing volume.

Table 1

Actual sizes of cylindrical seeds.

Material	Diameter (mm)	Length (mm)
Palladium	0.8	4.0
Silver	0.8	4.0
Titanium	0.6	4.0
Stainless Steel	0.7	5.0
Theraseed	0.8	4.5

Table 2

Average statistics for IRON images in Fig. 5.

Material	$\chi (\times 10^{-6})$	$\Delta\chi (\times 10^{-6})$	Y (mm)	Z (mm)	Contrast
Palladium	806	~815	12	14	32
Silver	-24	~-15	3.4	5.4	3
Titanium	182	~191	8.7	8.3	15
Stainless Steel	3520 to 6700	~5120	8.3	6.1	24
Therased	unknown	unknown	6.7	4.5	13
Gelatin/Tissue	-11.0 to -7.0	0	-	-	-