Published in final edited form as:

Magn Reson Med. 2018 June ; 79(6): 3122–3127. doi:10.1002/mrm.26981.

A spiral-based volumetric acquisition for MR temperature imaging

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Abstract

Purpose: To develop a rapid pulse sequence for volumetric MR thermometry.

Methods: Simulations were performed to assess temperature deviation, focal spot distortion/ blurring, and focal spot shift across a range of readout durations and maximum temperatures for Cartesian, spiral-out, and retraced spiral-in/out (RIO) trajectories. The RIO trajectory was applied for stack-of-spirals 3D imaging on a real-time imaging platform and preliminary evaluation was performed compared to a standard 2D sequence in vivo using a swine brain model, comparing maximum and mean temperatures measured between the two methods, as well as the temporal standard deviation measured by the two methods.

Results: In simulations, low-bandwidth Cartesian trajectories showed substantial shift of the focal spot, whereas both spiral trajectories showed no shift while maintaining focal spot geometry. In vivo, the 3D sequence achieved real-time 4-dimensional monitoring of thermometry, with an update time of 2.9–3.3 seconds.

Conclusion: Spiral imaging, and RIO imaging in particular, is an effective way to speed up volumetric MR thermometry.

Keywords

MR-guided Focused Ultrasound; Thermometry; Spiral Imaging

Introduction

MR-guided focused ultrasound (MRgFUS) is a promising non-invasive technique for cancer therapy, neural tissue ablation, and drug delivery across the blood brain barrier (1,2). Real time MR thermometry of the heated volume, usually based on the proton-resonance

frequency (PRF) shift (3), is a key aspect of these procedures. Early work in the field focused on 2D imaging, either of one slice or more recently, of a number of slices (4,5); however, the desire to monitor the entire insonicated volume and temperature field has led the field towards the development of rapid 3D methods (6–8). The ability to monitor insonications in 3D would speed up the low-power planning stages of FUS procedures, would ensure that the maximum temperature recorded by the FUS software is truly the maximum temperature change caused by the FUS system, and would aid in identifying and stopping off-target heating. Acquiring fully sampled 3D volumetric data to measure phase changes due to the PRF shift in response to heating is time consuming, however, and so fast methods must be developed in order to meet the spatial and temporal requirements for adequate monitoring of thermal therapy.

One approach used to speed up acquisitions in MRI is through accelerated scans, based on spatial or temporal undersampling (6,7). Parallel imaging is a method by which spatially undersampled data may be reconstructed by utilizing the redundant information imparted by multiple receiver coils. However, most of the hardware currently available for MRgFUS procedures is limited to a single channel, so parallel imaging approaches are largely precluded at this time. Temporally undersampled data can be reconstructed using a variety of techniques, from simple sliding-window approaches, to advanced reconstruction methods that use a model to guide the reconstruction of missing data, possibly based on heat transfer equations (6,9–11).

Another possibility to speed up acquisitions is to use more efficient trajectories for data collection. EPI sequences, for example, have been used to accelerate data acquisition for both 2D and 3D MR thermometry (6–8,12). Another option is to use the data acquisition efficiency of non-Cartesian trajectories in order to speed up acquisitions. Spiral trajectories, due to their data acquisition efficiency, are an attractive way in which to improve temporal resolution while maintaining spatial resolution in MR thermometry (13). Additionally, spirals have good robustness in the presence of motion and, importantly for MRgFUS, off-resonance does not cause a shift in the position of the thermal acoustic focus (focal spot) when using spirals, as it does for low bandwidth GRE and EPI-based methods (14,15).

The purpose of this study was first to develop a 3D spiral MR thermometry sequence based on the retraced spiral-in/out trajectory and to demonstrate that the sequence accurately depicts the thermal lesion in simulations. The second part of this work was to implement the sequence on a real-time platform and demonstrate its preliminary effectiveness in a set-up approaching clinical-relevance using an in vivo porcine model for MRgFUS thalamotomy.

Methods

The Retraced spiral-In/Out (RIO) trajectory

One attractive aspect of the commonly used spiral-out trajectory is its natural ability to acquire short echo times (TE). However, spiral-out trajectories are inefficient when used in late TE applications (such as those encountered in MR thermometry), because no data acquisition can occur prior to starting the spiral at the center of k-space (Fig. 1). The spiral-in/out trajectory (16) is capable of symmetrically sampling late TEs while maintaining many

of the benefits of spiral-out imaging. Furthermore, it was recently demonstrated that a particular class of spiral-in/out trajectories, the retraced in/out (RIO) acquisition, has the remarkable property of inherently compensating for much of image blur caused by T_2 decay, main field inhomogeneity, and concomitant gradient fields (16,17). A RIO scan is one in which each k-space point is traversed both when spiraling in and spiraling out, and the resultant signals are added together.

Simulation

A comparison of spiral-out, RIO spiral, and Cartesian scanning was performed through numerical phantom experiments. The simulations were performed by adding a small, Gaussian-shaped off-resonance source to otherwise on-resonance phantom data, sampling the data with either a spiral-out, RIO spiral, or Cartesian trajectory and reconstructing the result using conjugate phase reconstruction (18). A matrix size of 512×512 was used with an FOV of 224 mm^2 . The maximum value of off resonance added was equivalent to either a 10, 20, or 30 °C temperature rise, assuming a field strength of 3.0 T and $\alpha = -0.00909 \text{ ppm/}^\circ\text{C}$. α is the PRF thermal coefficient used to convert phase differences between images to measured temperature changes. Spiral trajectories were of either 4, 8, or 12 ms in duration, with the number of interleaves increased for the shorter-duration trajectories in order to maintain equivalent spatial resolutions for each trajectory. For this spiral-in/out design, an in/out trajectory – equal in duration to a fully-sampled spiral-out trajectory – is required to fully-sample k-space. Therefore, the comparison between trajectories of equal length is appropriate. The bandwidth of the Cartesian trajectory was either 250, 100, or 50 Hz/Px, to cover a range of bandwidths that might be found in standard EPI and low-bandwidth protocols. For each trajectory, one image was generated without the off-resonance source (a “cold” image) and one image was generated with the source (a “hot”) image. The cold image was subtracted from the hot image as would be done for a single baseline subtraction MR thermometry technique.

The deviation from the specified temperature, expressed as a percent, was then calculated to assess temperature accuracy of each method by dividing the maximum reconstructed pixel by the specified input temperature. In the same manner, the deviation from the specified full-width at half-maximum (FWHM) was calculated in order to assess changes in focal spot size. The ratio of the magnitude of the first sidelobe of the hot spot cross-section to the mainlobe intensity was calculated as an additional measure of reconstruction fidelity for each trajectory. Finally, the shift of the reconstructed focal spot was calculated as the Euclidian distance between the center of the reconstructed maximum-value pixel and the location of the specified maximum-value pixel.

Real-time platform and experimental setup

To test the sequence’s performance, the 3D RIO thermometry sequence was implemented on the RTHawk platform (HeartVista, Inc.) to enable real-time sequence control and monitoring of a FUS insonication. The 3D RIO sequence was implemented as a stack-of-spirals, with standard phase encoding in the through-plane direction. RTHawk interfaced with a GE Discovery MR750T 3T scanner at the UVA Focused Ultrasound Center, where an Insightec ExAblate 650 focused ultrasound transducer was used to induce focal heating.

All animal experiments were approved by and carried out under the guidelines of the University of Virginia Animal Care and Use Committee (ACUC). Three Yorkshire pigs weighing 15–20 kg were used for sequence evaluation. Non-ablative power settings were used to compare the temperatures measured by the 3D sequence to those measured by the standard 2D GRE thermometry sequence provided by Insightec. Briefly, a target within the thalamus was identified, and then insonicated at low power with monitoring performed by either the 2D or 3D method. After an appropriate cool-down period, the same spot was insonicated again with the same power settings and monitored by the alternate thermometry technique. Due to the temporal resolution of the 3D sequence, all insonications were 20 seconds long. Maximum temperature, measured by the single hottest pixel, and mean temperature, measured as the average of the 9 pixels surrounding the hottest pixel in a single plane, were recorded. Temperature standard deviation of each thermometry image set was measured as the mean standard deviation over time of a group of 9 pixels located within the brain away from the focal spot.

All ultrasound experiments required an initial craniotomy procedure to provide a cranial window for acoustic energy. Because of the flat contour of the porcine cranium, ultrasound energy cannot be focused as effectively in a transcranial fashion as it can be in humans. Following craniotomy, the scalp flap was sutured over the removed portion of the skull and the animal placed onto the FUS transducer such that the natural focus of the FUS system lies within the thalamus. Sequence parameters for 3D RIO thermometry were: FA = 10°, TR/TE = 20.1/12.8 ms, readout length = 8 ms, interleaves = 24 over a FOV of 280 mm² for a true in-plane resolution of 1.5 mm², reconstructed to 1.1 mm² to match the Cartesian acquisition, below. 3D phase encodes = 12 with through-plane resolution of 3 mm, so that through-plane FOV was 36 mm. The second, retraced acquisition of each RIO volume set was interleaved between base acquisitions, then the base and retraced data was combined in a sliding-window fashion so that the reconstructed frame rate was 2.9 seconds (true temporal resolution was 5.8 seconds). No post-processing off-resonance correction was used for any spiral data. Temperature maps were generated using a single baseline technique, using $\alpha = -0.00909$ ppm/°C. In one pig, a spectral-spatial pulse was used for water-only excitation in order to reduce artifacts stemming from fat, which necessitated an increase of TR to 22.7 ms and reconstructed temporal update interval to 3.3 seconds. Sequence parameters for the 2D thermometry method were: TR/TE = 27.6/12.8 ms, pixel bandwidth = 44 Hz/px, matrix size 256 × 128 over a FOV of 280 mm² for a resolution of 1.1 × 2.2 mm², reconstructed to 1.1 mm², slice width 3 mm, and update interval 3.5 seconds. T2-weighted images of the ablations were acquired at the end of the study.

Results

Figures 2 and 3 show simulation results of MR thermometry using spiral-out, RIO spiral, and Cartesian scanning. For nearly all cases, the RIO spiral trajectory more accurately represents the specified, true, temperature input than does spiral-out (Fig 2a). RIO spiral consistently underestimates the true value by 1–4%, whereas spiral-out overestimates the true value by 5–14%. In comparison, all Cartesian trajectories come within 4% of the true temperature (Fig. 2b), with an inclination to underestimation, similar to the RIO spiral results.

Together, the deviation from the specified FWHM (Figs. 2c,d) and sidelobe-to-mainlobe intensity (Figs. 3a,b) results indicate how well each trajectory represents the true, Gaussian input temperature function. The spiral-out trajectory has a tendency to narrow the mainlobe (Fig. 2c) and create stronger sidelobes (Fig. 3a) compared to the RIO trajectory, which is more accurate, except for a few cases. The Cartesian trajectory performs well in maintaining mainlobe FWHM (Fig. 2d), but strong sidelobes become apparent when position shifting of the hot spot becomes appreciable (Figs. 3b,d). While Cartesian trajectories showed significant position shifts of up to nearly 1.6 mm (Fig. 3d), all spiral trajectories displayed negligible position shifting (Fig. 3c).

Real-time in vivo thermometry images are shown in Figure 4. The focal spot is resolved in volumetric space with the spiral 3D sequence, and the ablation seen on the T2-weighted image corresponds well to the focal spot. Maximum, mean, and temporal standard deviations from each experiment are reported in Supporting Table S1, and scatter plots of this data is presented in Figure 5. The maximum temperatures measured by the 3D sequence correlate well with those measured by the 2D sequence.

Discussion

In simulations and through an in vivo experiment, we have demonstrated that the efficiency of spiral trajectories allows for 3D encoding while maintaining good temporal resolution. We have verified that spiral trajectories do not shift the position of the focal spot, in contrast to low bandwidth Cartesian imaging methods. Furthermore, we have shown that the RIO spiral trajectory performs well in this application and helps to maintain focal spot resolution, mitigating the possibility of blur caused by spiral imaging.

In the real-time implementation, the true temporal resolution (5.8–6.4 seconds) and SNR (temporal standard deviation 1.32 °C) achieved in this work do not reach the performance metrics of the current Cartesian technique (3.5-second framerate with a temporal standard deviation of 0.77 °C). However, the spiral sequence is 3D, and performance metrics for MR thermometry may vary in different settings and applications. Maximum temperatures correlated better between the two thermometry sequences than did mean temperatures, possibly due to the general mainlobe narrowing shown by spiral simulations in Fig. 2c. Qualitatively, spectral-spatial pulses improve image quality, but further evaluation of fat suppression methods is needed to determine whether it leads to quantitative improvements. Readout length and number of interleaves were chosen in this study to best balance SNR and image blur caused by inhomogeneity without performing off-resonance correction in a post-processing step. While longer readouts would lead to better temporal resolution, they would also test the off-resonance performance of the RIO technique to a greater degree. Increasing readout duration would result in a concomitant reduction in the number of shots required to fill k-space, and therefore improve the temporal resolution of the technique. In the future, off-resonance correction can be added to the spiral reconstructions, either with or without collecting field map information (17,21,22), in order to achieve this.

The RIO spiral trajectory is an appropriate choice for thermometric applications because it collects data more efficiently from late echoes due to symmetrical data sampling around the

echo. As Figure 1 shows, this allows for a shorter minimum TR, compared to a spiral-out gradient with the same TE. However, its main disadvantage is that it requires two signal averages (or alternatively, twice the number of interleaves) to achieve off-resonance correction. Here, we interleave the retraced trajectory acquisitions between the base acquisitions and update the images in a sliding window fashion, similar to (19). In this way, images are updated at the same frequency as the regular spiral-out acquisitions, albeit with some temporal blurring caused by the 2X temporal footprint required by the RIO technique.

In Cartesian scanning, the position shift of a given voxel is the ratio of the frequency shift of the voxel to the acquisition bandwidth. In EPI, which has been used for MR thermometry (6–8,12), the bandwidth in the phase-encoding direction is much smaller than in the readout direction; therefore, shift of the focal spot in EPI is commonly observed in the phase-encoding direction (14,20). In standard GRE sequences used for MR thermometry, low readout bandwidths are used in order to increase image SNR. For example, the readout bandwidth used for thermometry in neurological procedures at our institution is 44 Hz/Px (readout duration 22.7 ms). In these sequences, shift of the focal spot is observed in the readout direction. Shifts of the focal spot reported in the literature and observed at our institution are generally on the order of 1–3 mm, depending on maximum temperature reached. For thalamotomy procedures, this positional inaccuracy is very important and acts to extend procedure times as well as the number of insonications as the readout and phase encoding directions are switched during low power insonications to assess the shift before the high-power ablative insonication is performed.

A key advantage of spiral imaging is that while off-resonance can cause blurring, it does not shift the position of the focal spot, in contrast to EPI or low bandwidth GRE sequences. While this has been demonstrated previously, we have supported this fact here and have shown that the same holds true for RIO spiral imaging in simulation. With the spiral readouts used in this study, the amount of blurring caused by spiral imaging was minimal.

Many of the 3D techniques in existence for MR thermometry rely on EPI as it can very quickly cover large segments of k-space (9,11). While promising results have been achieved using EPI, there are several issues that must be addressed: First, as it has been established, the focal spot shifting problem must be accounted for in order for this tool to become clinically useful. Efforts to do so are underway (20). Second, while fast, EPI alone is not sufficiently speedy to collect all of the necessary 3D data within the time frame required. Efforts to speed up EPI-based techniques are underway, including advanced model-based reconstructions of undersampled data (9). Of course, in order for a 3D spiral-based technique to prove clinically useful, it also must be sped up somehow. A modest 1.8X (6.4s/3.5s) speedup of the described technique would bring it into competition with the clinically-used method, although a 3.5 second update interval itself has not been shown to be optimal and the true temporal resolution required may be longer. As has been discussed previously, increasing readout duration is one possible way to speed up the acquisition, albeit with a concomitant increase in off-resonance blurring. Here, we use a sliding-window to combine adjacent retraced data and improve the apparent frame rate, but model-based approaches to reconstructing temporally undersampled data are another possibility to speed up the acquisition. Yet another approach under investigation is to use statistical prediction

techniques to fill in the missing temporal data (15), and efforts to combine the methods can be found as well (10).

In conclusion, the efficiency of spiral trajectories over their Cartesian counterparts is an attractive way to obtain volumetric MR thermometric data while maintaining sufficient temporal resolution. The RIO spiral technique is naturally suited for this application due to the late TEs used for thermometry, and its use mitigates the natural disadvantage – blurring – that spiral imaging has traditionally suffered, resulting in sharp images of the focal spot resolved in 3 spatial dimensions with good temporal resolution.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Depiction of example gradients for (a) spiral-out, (b) spiral-in/out, and (c) Cartesian trajectories. The minimum TR for spiral-out trajectories is generally longer than that possible with Cartesian or spiral-in/out.

Figure 2.

Comparison of spiral-out, retracted spiral-in/out, and Cartesian scanning in a simulation of MR thermometry. For each trajectory, maximum temperature rises of 10 (blue), 20 (green), and 30°C (orange) were simulated. Spiral-out and RIO spiral results are presented in the left column (a, c), with spiral-out results in solid bars and RIO results in hashed bars for readout durations of 4, 8, and 12 ms. Cartesian results are presented in the right column (b, d) for readout bandwidths of 250, 100, and 50 Hz/Px. The simulated deviation from the specified maximum temperature is presented in the first row (a, b), and the deviation from the specified FWHM of input Gaussian function is presented in the second row (c, d).

Figure 3.

Further comparison of spiral-out, retraced spiral-in/out, and Cartesian scanning in a simulation of MR thermometry. The same display parameters described for Figure 2 are used here. The sidelobe-to-mainlobe intensity is presented in the first row (a, b), and the shift from the specified focal spot location is presented in the second row (c, d).

Figure 4.

In vivo experimental results. Magnitude and phase-based temperature map generated by the clinical 2DFT sequence (a), 3D spiral temperature map (b), 3D T2-weighted images acquired after ablation (c), and (d) the 3D temperature map of the hottest time frame overlaid on (c). The 3D sequence resolves the focal spot in 4 dimensions, but has lower SNR. The 3D shape of the focal spot matches the resulting ablation as seen on the T2-weighted images. (Figures cropped from a larger FoV.)

Figure 5.

Correlations between the maximum (left) and mean (right) measured focal spot data presented in Supporting Table S1. Slopes and R-squared values are shown for the linear fits to the data, indicated by the solid line in each plot. Additionally, the line $y = x$ is shown as the thin, dashed red line in each plot.