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Progress in Visualizing Turbulent Flow using Single-Echo Acquisition Imaging

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Abstract— MRI of flow remains a challenging problem despite significant improvements in imaging speeds. For periodic flow the acquisition can be gated, synchronizing data acquisition with the flow. However, this method fails to work if the flow is sufficiently fast that turbulence occurs, or when it is sufficiently fast that blurring occurs during the excitation of the spins or the acquisition of the signal. This paper describes recent progress in employing a very fast MR imaging technique, Single Echo Acquisition Imaging (SEA-MRI) and spin-tagging to visualize very rapid and turbulent flow patterns. Demonstrations are done on a separating channel phantom with input flow rates ranging from zero to over 100 cm/sec. Spin-tagging enables a "texture" to be placed on the spins, enabling clear visualization of the complex flow patterns, and in some cases measurement of the flow velocity.

I. Introduction

Any imaging technique has a true temporal resolution limited by the "shutter speed", the total time to acquire all the raw data in the image. This is the limiting factor in measuring rapid kinematics. For *periodic* motion, the MRI acquisition can be gated to be synchronous with the motion, enabling imaging with apparent temporal resolution that is very fast, but has in reality been acquired over many periods of the motion. Cardiac imaging, BOLD fMRI and dynamic contrast enhanced imaging are examples of current applications of dynamic imaging[1] } [2, 3]. The first two are periodic, one naturally and one through paradigm design, and the other is sufficiently slow as to be accessible through modern pulse sequences. However, as MRI evolves into a functional imaging tool, the potential for using MRI to image extremely rapid, *non-periodic* or one-time events is of growing interest. The potential to study millisecond rate kinematics with MRI would open up a variety of potential applications. An extremely fast imaging technique could allow MRI of turbulent flow in stenotic vessels [4] and in microfluidic lab-on-a-chip devices where chaotic flow is desired for mixing [5, 6], or to follow millisecond kinetics in chemical reactions [7], or even to enable imaging of destructive events or single-shot imaging of pressure waves in MR elastography [8]. Emerging applications, such as hyperpolarized 13C imaging, which has the potential to enable direct molecular imaging using MRI[9], will require the *entire imaging study* to be completed in 10s of seconds rather than 10s of minutes, placing a premium on dynamic MRI methods.

Particle image velocimetry is an effective technique for visualizing flow in microchannels, but suffers from some disadvantages such as the need for optically clear channels and the need for exogenous contrast agents (seeding the flow with particles). Importantly, MRI is well-known for the wide-variety of endogenous contrast mechanisms available to study systems, including chemical shift mechanisms and direct imaging of flow velocity through phase contrast. NMR and MRI are being investigated as sensors for microfluidic devices and as a technique for characterization of the devices themselves [10]. However, existing MRI techniques suffer from long acquisition windows as described above and cannot approach the temporal (near-msec) resolution that is necessary for the elucidation of multiphase flow phenomena [11]. An ultra-fast MRI method would provide a new tool for the development and characterization of not only fluidic devices, but a new tool for studying and engineering many flow related devices.

II. Methodology & Theory

A. Single Echo Acquisition Imaging

To form a conventional phase encoded $N_p x N_f$ (*number of phase encoding steps* x *number of frequency encoding samples*) MR image, appropriate RF excitations and gradients are applied, an echo is "read-out" by sampling it N_f times, and the entire experiment is repeated N_p times – once for each phase encoding gradient strength. Partially parallel imaging methods such as SMASH and SENSE have been very effective in reducing imaging times for a given pulse sequence[12, 13]. These methods reduce imaging time by simultaneously receiving MR signals from multiple elements in an array of sensors, reducing the number of phase encode lines needed to form an image of a given spatial resolution by a factor up to the number of coils. Using arrays of four to eight coils, acceleration factors of two to three have become common in clinical applications. This places SEA imaging in context as a completely parallel imaging method in which phase encoding is completely eliminated, relying on the signal localization of an array of coils to define the image in one direction.

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In Single Echo Acquisition (SEA), slice selection and frequency encoding are performed using standard gradient methods, with the frequency encoding along the long axis of the array elements and slice selection in the coronal plane, parallel to the array. The phase encoding is eliminated and replaced by the spatial localization provided by N_p narrow, parallel and closely-spaced array elements [14, 15].

Using the prototype 64-channel receiver constructed in-house, the signals from each of the 64 coils are simultaneously received and digitized. A 1-D FFT is performed on the echo received from each coil, the resulting 64 images stacked into a $64xN_f$ matrix, and the matrix interpolated to $N_f xN_f$ for display.

B. Spin-tagging pulse sequence

A conventional non-refocused gradient echo pulse sequence was used, modified to include spin-tagging [16, 17] and a phase compensation gradient pulse rather than a phase encoding table. Spin-tagging was performed using DANTE RF pulse trains [18] where the pulse-width was modified rather than power levels. Initially a selectable series of excitation/acquisitions were performed following the initial DANTE train. Typically 64 echos were obtained after each tag, followed by a delay to enable relaxation.

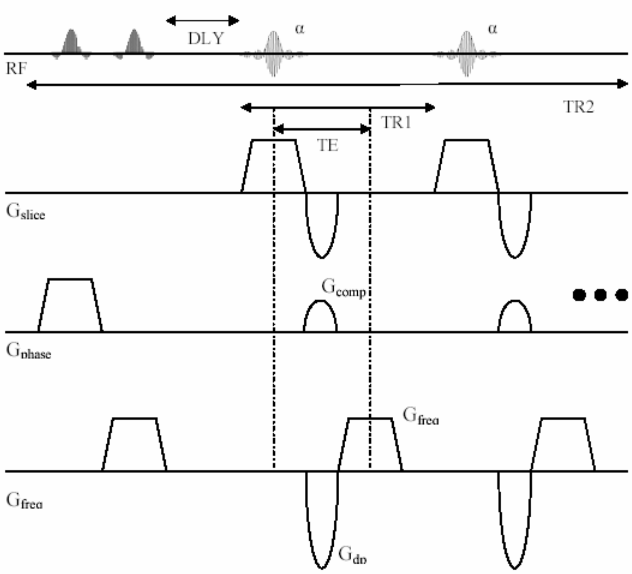

Figure 1. Basic Spin-tagging sequence, with two-dimensional DANTE pulse train preceding a recalled gradient echo sequence.

C. Flow Phantoms and Procedure

To validate the methods two rotating gel phantoms were constructed as shown in Fig. 2a and 2b. These phantoms were rotated using an analog controlled motor driving a string and wheel system. These phantoms have previously been used for phase contrast velocity measurements using SEA imaging, but spin-tagging methods may prove more useful due to the difficulty in using subtraction techniques in SEA imaging of non-periodic flow. Subtraction techniques are typically used to eliminate the effects of shim and RF coil phase effects in phase contrast techniques.

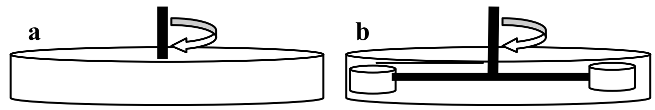

Figure 2. Rotating dish (a) and cup (b) phantoms for calibrating and validating velocity measurements. Gelatin was mixed with distilled water and different concentrations of $CuSO_4$ to optimize tag decay and signal strength.

A separating channel flow phantom similar to that illustrated in Fig. 3 was used to test and demonstrate the flow visualization. Flow was provided by a Cole-Parmer Masterflex peristaltic pump. Flow rates at the input were constrained by the 3/16" tubing, but flow rates at the input could exceed 1 meter/sec, based on the measured flow volumes through the phantom. The flow rates in the 3/16" tubing for six different settings of the pump, and the corresponding flow velocities in the input channel are given in Table 1. Distilled water was used in these initial experiments, primarily to enable slow decay of the spin-tags.

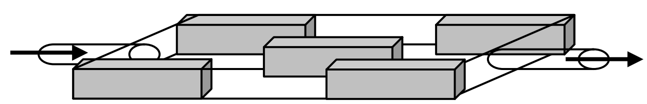

Figure 3. Separating channel flow phantom, overall dimensions 13 x 8 cm wide, matched to the 64 channel coil array outer dimensions. The phantom is 0.5 cm high.

Table 1. Flow volumes and the corresponding flow velocities at the input tube and initial channel in the flow phantom (average value).

Pump Setting	Flow ml/sec	Entry Tube cm/sec	Entry Channel cm/sec (ave.)
0	0.0	0.0	0.0
1	3.3	17.0	2.5
2	7.7	43.2	6.3
3	12.5	70.2	10.2
4	15.6	87.7	12.8
5	20.0	112.	16.4

Single echo acquisition magnetic resonance imaging was performed at frame rates as high as 200 frames per second [19]. A spoiled gradient echo sequence was used, with TR = 5 ms., TE = 3 ms. The FOV was 14 x 14 cm, with an acquired matrix size of 128 in the frequency encoding direction, and 64 in the 2nd direction due to the use of 64 elements for image encoding with SEA imaging. The entire phantom was excited. The acquisition window was 0.64 msec, with a spectral width of 100 KHz. Final images were interpolated to 256x256. The pulse sequence of Figure 1 allows a delay (DLY) between the application of the spin-tags and a series of gradient echo acquisitions. Typically 64 acquisitions were obtained following each spin-tag.

III. RESULTS & DISCUSSION

Figure 4 shows a Single Echo Acquisition MR image of the separating channel phantom and a sketch of the phantom. The red box corresponds to the footprint, or outer dimensions of the array coil. Because the SEA image has lower resolution in the array encoded direction (vertical in Fig. 4) diagonally oriented spin-tags were used. The spin tags were approximately 2 mm wide with a separation of 6 mm. The duration of each set of spin-tags was 14 msec, followed by a series of gradient echo acquisitions (typically 64), each with 5 ms TR and 3 ms TE. Thus, images were obtained at 200 frames/second in between the tagging pulses.

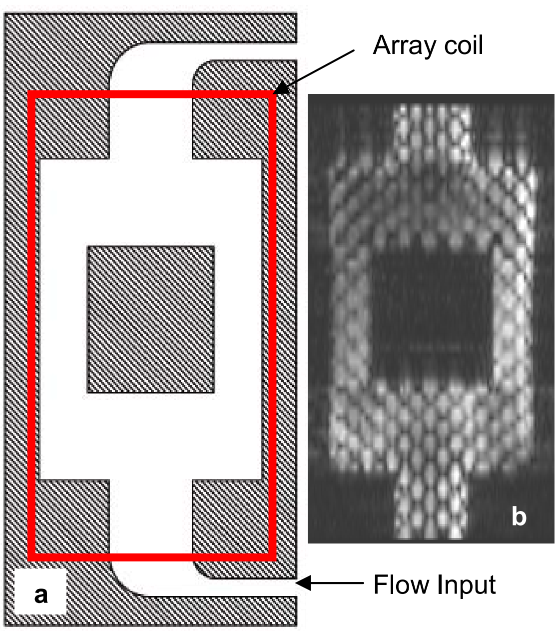

Figure 4. Sketch of the separating channel flow phantom showing the actual configuration of the input and output channels (a), and a SEA MR image of the phantom with diagonal spin-tags (b). The red box indicates the location of the 64 element SEA coil array.

Figure 5 shows a series of frames from a movie. Two tag then acquire x 64 data sets were acquired successively, followed by a 3 second delay to allow for T_1 decay. During the delay, the flow velocity was increased. Each row of three frames in Fig. 5 represents the 1st, 10th and 20th frame following the spin-tags at the six velocity settings corresponding to the six rows in Table 1. As a TR of 5 msec was used, the middle column corresponds to 50 msec following the tags, and the third column corresponds to 100 msec following the tags. While the results are somewhat difficult to illustrate with isolated frames, several interesting results are observed.

In row 2, the first with a non-zero velocity, the input flow stream follows the left side of the channel, as expected from the geometry illustrated in Figure 4. It is interesting that the flow is retrograde on the right side. As the flow velocities increase, several features become apparent. First, a region of essentially zero flow is observed in the "shadow" region immediately above the center obstacle. The tags persist essentially undisturbed in this region. Eddies in the flow are easily seen in the animations, in particular in the lower left corner. The tortuous nature of the flow in the outlet channel is also clearly observed. Flow rates can be estimated by following a point in the spin-tag matrix while it is intact. In the 100 msec between the first and the 20th tag in row two, the fastest flow observed in the inlet channel moved approximately 1 cm, corresponding to a flow velocity of 10 cm/sec, approximately ½ that of the input flow tube (row 2 of Table 1). This corresponds to the observation from the animations that despite having a much broader channel, the flow streams on the left side of the channel, decreasing only about 50 percent from the initial velocity. As the flow velocities increase, imaging continues to be relatively artifact free, unlike imaging with conventional phase encoding. At the higher flow rates the spin-tags are increasingly blurred due to the relatively long acquisition and are quickly lost due to the rapid mixing in the flow field. However, they do provide a "texture" to the flow which is

This preliminary work has indicated the need for a number of improvements. First, a faster method of applying the spin tags would be helpful. Similarly, in order to obtain high frame rates a single lobe RF pulse was used for excitation, exciting the entire 5 mm thick phantom. Thinner slices will also require higher power. Finally, extending the method to curved surfaces, such as concentric cylinders inside a vessel, will require a cylindrical coil.

We are investigating converting the system to a transmit/receive configuration. This will provide higher B_1 levels for the excitation pulses, and will overcome inherent difficulties when using curved arrays for SEA imaging. While the results presented here are preliminary, they indicate the capability of Single Echo Acquisition imaging to capture flow behavior at high velocities. Unlike conventional methods, all of the image information is acquired during a single echo, thus the "bandwidth" of the method is higher than other methods. This could provide a new method for imaging turbulent flow, such as in stenosed vessels, where conventional phase encoded methods can fail.

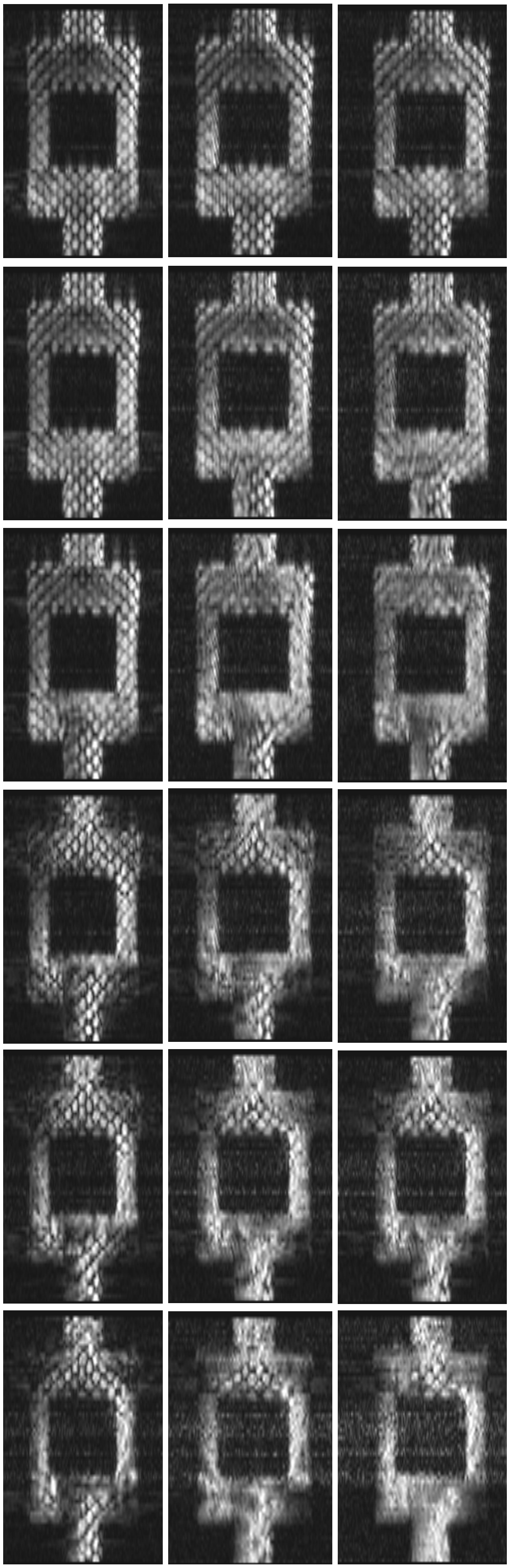

Figure 5 (left). 18 frames from a series of 1024 obtained in eight groups, with a 3 sec delay between groups to allow T_1 decay. Each group was acquired at 200 frames per second. Each row corresponds to an increasing velocity, given by the six rows in Table 1. The 1st, 2nd, and 3rd columns are the 1st, 10th and 20th frames acquired following the application of the spin-tags. While not fully appreciated in individual frames, flow distribution, eddy currents, and jets can be readily observed and followed.

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