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Small field of view imaging using wavelet encoding with 2 dimensional RF pulses and gradient echo : phantom results

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**SMALL FIELD OF VIEW IMAGING USING WAVELET ENCODING WITH 2
DIMENSIONAL RF PULSES AND GRADIENT ECHO: PHANTOM RESULTS.**

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ABSTRACT:

Object: The objective of this work is to propose an imaging sequence based upon the wavelet encoding approach to provide MRI images free from folding artifacts, in the small Field Of View (FOV) regime, such as dynamic magnetic resonance imaging (MRI) studies.

Materials and Methods: The method consists of using a 2D spatially-selective RF excitation pulse inserted into a gradient echo pulse sequence to excite spins within a determined plane where wavelet encoding is achieved in one direction and slice selection is performed in the second direction. Wavelet encoding allows for spatially localized excitation and consequently restricts the spins excited within a reduced FOV. It consists of varying, according to a predetermined scheme, the width and position of the profile of the so-called fast RF pulse of the 2D RF excitation pulse, to obey wavelet encoding translation and dilation conditions. This sequence is implemented on a 3 Tesla whole body Siemens scanner.

Results: Compared to Fourier encoding, the proposed technique tested on phantoms with different shapes and structures, is able to provide gradient-echo reduced FOV images free from aliased signals.

Conclusion: Wavelet encoding is suitable for small FOV imaging in dynamic MRI studies.

Key words: wavelet encoding; small FOV imaging; spatially-selective 2D RF excitation; dynamic MRI.

INTRODUCTION:

Several magnetic resonance imaging (MRI) applications, such as cardiac imaging, interventional, and functional MRI, utilize small Field Of View (FOV) imaging to perform dynamic MR studies [1]. In cardiac imaging, the entire chest is typically within the FOV while the heart occupies a small part of the FOV. In MR temperature mapping monitoring procedures, such as focused ultrasound ablation of tissue, only the therapy volume, which occupies a small portion of the FOV, is of special interest. In functional MRI of pre-surgical planning, the region surrounding the tumor may be the only part of the FOV that has clinical value. In studies such as these, a reduction of the size of the FOV covering with sufficient resolution the region of interest (ROI) is required; otherwise the resolution of the organ occupying a relatively small part of the imaged FOV is not sufficient. However, reducing the imaging FOV with Fourier encoding results in aliased images in the phase encoding direction originating from the “wraparound” or folding artifacts [2]. In addition to the FOV reduction, the region of interest might be smaller than the imaged organ where only a portion of encoding steps is updated.

A number of solutions have been proposed to solve the folding problem, such as reduced field-of-view methods [3], and the UNFOLD technique [4]. There is, however, a simpler approach which consists of avoiding this problem altogether by only exciting the signal inside the ROI using different encoding techniques. In this scope, the use of a 2D excitation RF pulse is preferred since it simultaneously excites spins within a selected column. Finsterbusch et al. proposed the use of a 2D RF pulse excitation with line scanning in functional neuro-imaging of the human motor cortex [5]. Zhao et al. combined the 2D RF pulse excitation with the UNFOLD approach to suppress the residual artifacts in MRI-based temperature mapping studies [6]. Both propositions allow for a better temporal resolution than conventional gradient-echo imaging by restricting the FOV, while maintaining high spatial resolution. Wavelet encoding is another alternative, since it localizes regions of interest to be excited and consequently allows for FOV reduction without folding. Wavelet encoding is derived from wavelet transform which uses prototype functions called wavelets, seen as filters with variable spatial width and position, to divide a given input spatial function into a set of predetermined subspaces. This operation is a linear transformation from the input spatial domain to the

wavelet domain [14]. The variations of the position and the spatial width of the filters are determined through translation and dilation of the wavelet functions, respectively. In MR, wavelet encoding is performed through RF pulse manipulations, which play the role of the wavelet functions. Wavelet translation and dilation are performed by shifting the frequency of the RF pulse and varying the strength of the corresponding localization gradient, respectively. Most of the proposed wavelet encoding sequences relies on spin-echo based sequences [7, 8], where the excitation RF pulse is used to achieve wavelet encoding, which replaces the phase encoding, and the refocusing RF pulse is used for slice selection. However, using spin-echo sequences is a limiting factor in high speed imaging where gradient-echo based sequences are preferred especially at high B_0 field [9]. One possible solution to this limitation is to use a 2D spatially selective RF excitation pulse to allow for column selection [10]. The first dimension is attributed to FOV reduction selection with wavelet encoding and the second dimension is used for slice selection.

Several k-space trajectories are available to use [11]. The blipped echo planar imaging (EPI) trajectory is chosen for our 2D RF pulse since it allows for a straightforward wavelet encoding implementation. The so-called fast RF pulses of the 2D RF pulse along with the corresponding zig-zag gradient are used for wavelet encoding, and the slow RF pulse of the 2D RF pulse is left for slice selection. As for the wavelet functions, we chose Haar wavelets, due to their simplicity of implementation. Their shapes resemble the profiles of the sinc RF pulses [12].

Following the two dimensional RF pulse, a gradient echo signal is acquired by activating a standard readout gradient applied in the remaining orthogonal direction. Wavelet encoding provides images with low signal to noise ratio (SNR) as compared to Fourier encoding [13]. However, it provides images with better SNR than line scanning techniques [14] and does not rely on aliasing correction methods, as for the combined 2D RF pulse with UNFOLD method, where restrictions are placed on the profile of the main excitation lobe of the 2D RF pulse to avoid aliasing from the side lobes [15]. It remains that side lobes in the slice-select direction are a potential source of undesired aliasing in the proposed encoding method and need to be saturated before encoding. This is

performed by using spatial saturation RF pulses on the two sides of the main lobe in the slice direction. The proposed gradient echo wavelet encoding technique (GE-WE) using a 2D RF excitation pulse is successfully implemented on a 3 Tesla Siemens scanner and phantom tests are reported. Alias-free small FOV images that are suitable for MRI-based dynamic imaging studies are obtained and compared to the standard gradient-echo images.

THEORY

Wavelet encoding has been first proposed by Weaver and Healy as an alternative to phase encoding technique in a spin-echo MR sequence to reduce acquisition time and motion artifacts [16]. In their method, phase encoding is replaced by wavelet encoding, where the excitation RF pulses are manipulated to play the role of the Haar functions to achieve the encoding. This method has been implemented by Panych et al. using different wavelet functions [17]. Since then, the method has not seen widespread application, mainly due to the low SNR of the wavelet encoding images compared to the regular Fourier encoding methods. It has shown usefulness in multi-slice imaging where an improvement of SNR is obtained [18]. In addition to imaging, wavelet encoding has been proposed in magnetic resonance spectroscopic imaging (MRSI) to reduce acquisition time and voxel contamination [12, 19]. Here we propose wavelet encoding as a technique for low resolution images in the small FOV regime. The theory behind the development and implementation of wavelet encoding in MR, briefly summarized here, is discussed in detail in previous works [12, 16, 19].

Wavelet encoding is based upon the discrete wavelet transform. A linear transformation from the space domain to the wavelet domain is performed using dilated and translated scaling and wavelet functions. This transform achieves a division of an input finite space function to a set of output sub-spaces with different sizes and locations [20]. The wavelet dilation determines the size of the sub-space, while the translation localizes its position [12, 16]. The number of wavelet dilations, which sets the number of translations, is determined by the desired spatial resolution. Similar to the Fourier synthesis, which performs an inverse Fourier transform on the acquired $\mathbf{K}$ -space data (Fourier coefficients) to obtain the spatial image, an inverse wavelet transform is

performed on the acquired sub-spaces (wavelet coefficients) data to perform the same task [20]. The wavelet dilations and translations are achieved by changing the localization B_0 field gradient strength and by shifting the frequency of the selective RF pulse, respectively [12, 19].

The small tip-angle excitation approach developed by Pauly et al. [21] briefly summarized here, is used to generate the 2D RF excitation pulse used in wavelet encoding. The $\mathbf{K}$ -space trajectory between t_0 and t_1 , describing a low flip angle spatially selective RF excitation $B_1(t)$ in the presence of time-dependent magnetic field gradients $G(t)$ is given by:

$$k(t) = -\gamma \int_{t_0}^t G(t') dt' \quad t_0 \leq t \leq t_1 \quad (1)$$

This represents a one-dimensional line in the three-dimensional $\mathbf{K}$ -space along which the effective gradient integral accumulates during the evolution of the RF pulse. The excitation profile of a magnetization at location r assumed to be at thermodynamic equilibrium before excitation ($M_0(r)$) is given by [21]:

$$M_{xy}(r) = i\gamma M_0(r) \int W(k) S(k) \exp(ir \cdot k) dk \quad (2)$$

where $S(k) = \int_{t_0}^{t_1} |\dot{k}(t)| \delta(k(t) - k) dt$ represents the sampling function in excitation $\mathbf{K}$ -space, ($\delta(k)$ representing the Dirac function), and the spatial frequency weighting function $W(k)$, given by $W(k(t)) = B_1(t) / |\gamma G(t)|$, describes the B_1 -field along the trajectory as a function of k .

If the k -space is completely covered by the trajectory the resulting excitation profile P is given by the Fourier transform of W . The Fourier transform should be chosen as the weighting function if a specific RF excitation is desired.

In practice, sampling is restricted to a finite region in $\mathbf{K}$ -space. As a consequence, truncation and blurring appears in the excitation profile P . The effects become more

pronounced for smaller sampled regions. Columnar excitation volumes lead to an additional problem as the required weighting function $W(k)$ does not vanish on a two-dimensional area in $\mathbf{K}$ -space. Because the one-dimensional trajectory $\mathbf{K}(t)$ covers the $\mathbf{K}$ -space only along discrete lines, the convolution of the Fourier Transform of the weighting function with the Fourier Transform of the sampling function (i.e., a function of discrete lines itself), results in an excitation profile with periodic “side” excitations (side lobes). Whereas their specific shape depends on the chosen trajectory, their distance increases for higher sampling densities in $\mathbf{K}$ -space in accordance with FT properties.

The two dimensional $\mathbf{K}$ -space coverage might be achieved using different trajectories. In our application we have chosen the blipped echo planar trajectory since it allows for the application of the wavelet encoding (dilation and translation) along the direction of the zig-zag gradient and the slice selection along the direction of the blipped gradient. The wavelet translation is performed by shifting the central frequency of the fast RF pulse of the 2D RF pulse, whereas the dilation is achieved by changing the strength of the zig-zag gradient according to a specific pattern detailed elsewhere [12, 19]. Figure 1 displays simulation results of the 2D RF pulses used for wavelet encoding, along with the profiles of their fast RF pulses, compared to the wavelet and scaling functions [12, 19]. The figure also displays the corresponding blipped and zig-zag gradients.

MATERIALS AND METHODS:

We have developed the small FOV WE-GE technique by modifying a gradient-echo sequence to acquire 2D slice selective WE-GE images. Figure 2 displays the single-slice WE-GE sequence consisting of outer-volume saturation (SAT), 2D RF excitation (dashed box), and frequency-encoded gradient echo, as well as a schematic representation of the desired FOV, the wavelet encoding line excitations, the side excitations, and the RF saturation areas. For the 2DRF excitation pulse, six lines in the blipped echo planar trajectory are used to excite a column volume with the slice thickness and the FOV in the wavelet (phase) encoding direction set to the full width at half maximum (FWHM) of the profiles of both the slow RF pulse in the blip direction, and the fast RF pulse in the zig-zag direction (Figure 3). Sampling $\mathbf{K}$ -space trajectory starts from its center, forcing one of the six fast RF pulses to be split into two halves and placed at the tails of the slow RF pulse (Fig. 1). In the slice (blip) direction side excitations are generated above and below

the image section (Fig. 1). They are suppressed with the use of three sinc RF pulses with 5 ms duration and 3 KHz bandwidth, in each saturation region. Spoiler gradients are applied in three orthogonal directions with alternating directions. Two types of 2D RF pulses with a sinc function for the slow RF pulse using a Shinnar-Leroux algorithm [22] are generated. Each 2D RF pulse is composed of six fast RF pulses, each of 1.5 ms duration and 3 KHz bandwidth. The profiles of the two fast RF pulses are single band and dual band profiles corresponding to the Haar wavelet and scaling functions, respectively (Fig. 1). To achieve spatial encoding in the wavelet direction, dilations and translations of the dual band RF pulses, as detailed previously [12, 19], are achieved by increasing the selection gradient strength and shifting the central frequency of RF pulses, respectively. All calculated 2DRF envelopes are filtered with a Hamming filter to smooth out the transition bands. This is especially useful for the dual band ones to reduce tail artifacts. Slice shift is performed as follows: the frequency value corresponding to the desired slice shift is calculated. The phase value corresponding in time to the middle time position of each fast RF pulse is retrieved from the calculated frequency and added to the corresponding fast RF pulse. The developed WE-GE sequence is implemented on a 3.0-T whole-body MRI system (Tim Trio, Siemens, Erlangen, Germany) equipped with 40 mT/m gradients in the X, Y directions and 45 mT/m in the Z direction, with a maximum slew rate 180 T/m/s in the X and Y directions and 220 T/m/s in the Z direction. All measurements are performed with the use of the standard Siemens transmit-receive volume head coil. Image processing is adapted to the requirements of the WE-GE data by replacing the Fourier Transform in the direction of the wavelet lines by the inverse wavelet transforms using Haar functions.

RESULTS:

Figure 3 show the performance of the saturation RF pulses to suppress the signal that originated from the side lobes of the 2D RF pulse as well as the magnetization profiles of Haar wavelets in a spherical water phantom (diameter 150 mm) obtained with a 2DRF pulse (12.8 ms duration, 6 lobes) using a spin-echo sequence (FOV = 180 mm, slice thickness = 10 mm, TE/TR = 24/1000 ms, image size 128 by 128). A gradient echo

image is acquired first using the following parameters FOV: 400mm, slice thickness: 10mm, TR: 20ms, TE: 5ms, flip angle: 40°, 256x128. It is used in Figures 4 and 5, which show phantom results using the WE-GE sequence compared to the standard gradient-echo sequence. The acquisition parameters are: FOV =180 mm with 128x128 matrix size in figure 4, and 90 mm with 64x64 matrix size in figure 5, slice thickness: 10 mm TE: 9.15 ms TR: 250 ms, and flip angle: 50° for WE-GE images and 25° for gradient-echo images. The imaged phantom consists of a cylinder filled with doped water having refined structures and features. The phantom results show that WE-GE provides images without folding compared to the regular gradient-echo sequence.

DISCUSSION:

As shown in Figures 4 and 5, a few artifacts (strips in wavelet lines due to variation in signal amplitudes) remain in the WE-GE images due to two reasons; the first one is the inverse wavelet transformation, which uses the Haar scale and wavelet functions set to dual boxcar [1 -1] and boxcar [1 1], respectively [12, 19]. As shown in Figure 1, the areas of the bands of the RF pulses shown in blue (real) and red (imaginary) are not equal to the areas of the corresponding boxcars (Haar) shown in green. This is mainly due to the large transition band and the curved edges of the RF pulse profile. Longer RF pulses are required to better approach a boxcar shape. The second reason is the performance of the saturation RF pulses which is degraded if the saturation area is very large. This is mainly due to the high B_0 field where artifacts are more pronounced with gradient-echo sequences [23].

As expected the signal-to-noise ratio (SNR) of the WE-GE image is approximately 12% at high resolution (128x128) and increases to 65% at low resolution (64x64) compared to the SNR of the gradient-echo images.

However, problems concerning artifacts of saturation RF pulses, 2D RF pulse duration, and SNR need to be addressed before targeting specific applications.

CONCLUSION:

The main objective of this work is to provide free-folding images in a small FOV regime using a method based upon a combination of wavelet encoding with 2D RF pulse and gradient-echo. The preliminary phantom results show that the proposed method achieves this task. However, this project is still in its debut, and several problems need to be solved before targeting specific applications. The improvement will mainly concern skipping in real time wavelet encoding steps with weak SNR. Such a useful approach will definitely improve the performance of the proposed technique in term of SNR and acquisition time. Small FOV imaging is generally performed at low spatial resolution. In this manner, WE-GE provides images free from aliasing with acceptable SNR compared to phase encoding gradient-echo images. However, problems concerning artifacts of saturation RF pulses, 2D RF pulse duration, and SNR need to be addressed before targeting specific applications. To reduce the number of the saturation RF pulses, cosine modulated RF pulses will be incorporated. This will consequently reduce the minimum TR. The latter will be reduced by reducing the duration of the 2D RF pulse using multi-transmit capabilities available on our Siemens scanner. In order to increase the SNR, the Donoho approach will be integrated into the sequence acquisition where wavelet domain data with weak signal will not be acquired [24]. In this manner, acquisition time will be further reduced with an increase in SNR. To further reduce acquisition time, we are planning to incorporate parallel imaging in the wavelet encoding direction [25]. As for image artifacts originated from the wavelet shapes, we plan to use other wavelets with smoother decay and shorter duration [26].

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Figure captions:

Figure 1:

- A) RF and gradient diagram of 2D RF pulses (sinc and dual sinc functions) with echo planar excitation trajectory. The zig-zag gradient is used for wavelet encoding and the blip gradient for slice selection.
- B) Simulated results of the profiles of the 2D RF pulses.
- C) Profiles of the main lobes (real: blue, imaginary: red) summed across the slice direction compared to the wavelet (boxcar) and scale (dual boxcar) Haar functions (green).

Figure 2:

- A) Wavelet encoding sequence diagram. Wavelet encoding is performed in the zig-zag direction and slice selection in the blip direction. Saturation RF pulses are used to eliminate signals from side lobes. Gradient echoes are acquired in the readout direction.
- B) Schematic representation of the image section (FOV) using wavelet encoding, 2DRF excitations, side excitations and saturations. N consecutive wavelet encoding steps are performed in the wavelet direction. At each step, a portion of the FOV (shaded regions) is excited and the rest of the FOV is left unexcited (white portions) according to the dilation and translation variables.

Figure 3:

Magnetization profiles of Haar wavelets (a: single band, c: dual band) and effects of the saturation RF pulses on the side lobes are shown in b and d.

Figure 4:

Gradient echo image (B) acquired at 3T scanner with the dashed box showing the position of the FOV for the WE-GE and GE sequences. Small FOV WE-GE image (A) with no folding compared to the standard gradient-echo image (C).

Figure 5:

Gradient echo image (B) acquired at 3T scanner with the dashed box showing the position of the FOV for the WE-GE and gradient-echo sequences. Small FOV WE-GE image (A) with no folding compared to the gradient-echo image (C).