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**WAVELET ENCODING GRADIENT ECHO IMAGING SEQUENCE USING
REAL TIME DE-NOISING METHOD FOR ACQUISITION TIME REDUCTION.**

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ABSTRACT:

Object: To reduce acquisition time and increase signal-to-noise ratio (SNR) of the wavelet encoding gradient echo (GE-WE) sequence used in small Field Of View (FOV) dynamic magnetic resonance imaging (MRI).

Materials and Methods: A GE-WE imaging sequence acquires wavelet lines from a 3 Tesla scanner. Those with intensity below a given threshold are skipped in real-time, improving SNR and reducing acquisition time.

Results: The SNR of GE-WE images increases by approximately three times in simulation, while the acquisition time reduction ranges from 5-10% on phantom tests.

Conclusion: This technique improves the SNR of GE-WE images, while reducing acquisition time.

INTRODUCTION:

We have recently presented a wavelet encoding gradient-echo imaging sequence (GE-WE) as an alternative to Fourier encoding in acquiring magnetic resonance (MR) images free from folding artifacts in a small field of view (FOV) regime [1]. However, the proposed method suffers from low signal to noise-ratio (SNR) as compared to Fourier encoding. Several post-processing approaches have been proposed to increase the SNR of the wavelet encoded MR images. These methods use thresholding techniques to remove, in post-processing, any wavelet line with signal intensity below the noise level [2]. As a consequence the SNR of the images is increased.

The technique proposed in this paper is similar to the one above but applied in real-time, leading to a distinct advantage over the post-processing techniques. While the SNR gain is similar between the two, applying the technique in real-time allows the sequence to adapt to the particular form of the object/organ being imaged by not acquiring wavelet lines belonging to regions where there is little or no signal to be acquired. This leads to a decrease in the time required to acquire an image while having a minimal affect on the image quality and simultaneously increasing the SNR.

The proposed technique is successfully implemented on a 3 Tesla Siemens scanner and phantom tests are reported alongside simulation results.

THEORY

It is well known that the SNR in wavelet encoding MR images (SNR_{WE}) is lower than the SNR of Fourier encoding (SNR_{FE}) by the following factor [3, 4]:

$$SNR_{WE} \approx \sqrt{\frac{3}{N}} SNR_{FE} \quad (1)$$

where N is the image resolution corresponding to the number of acquired wavelet lines.

The properties of wavelet transform have allowed the development of several image de-noising approaches [2, 5, 6]. These can potentially be applied in the context of

MRI to similarly reap SNR benefits. They act on the wavelet domain data once it is fully acquired and remove lines which contain mostly noise by activating adaptive filtering techniques based upon variable thresholding values. Since the proposed GE-WE sequence acquires wavelet domain lines one can better exploit the usefulness of these de-noising approaches, and use them in real-time by processing the data while it is acquired. To follow the same thresholding principle as the methods above we propose a similar, yet simpler approach. It is based on the ratio of the maximum line intensity (representing the useful signal) over the average signal intensity of the line (representing noise). The threshold variable is given by:

$$skip = \begin{cases} 1 & \text{if } avg * val > m \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Where *avg* is the average of wavelet line, *val* is the value entered by the user, and *m* is the absolute value of the maximum intensity of the line. If the value for *skip* is 1, then the acquired line is supposed to mostly contain noise, and replaced in the wavelet domain by zeros. If the value for *skip* is 0, then the acquired line contains significantly more signal than noise, and is retained in the wavelet domain. It is important to note that the value entered by the user, *val*, in arbitrary unit, is also proportional to the maximum intensity over average signal ratio. Effectively, Equation 2 represents a given noise baseline, derived from each averaged wavelet line termed as *avg* and scaled by the manually adjusted factor *val*.

If the acquired line which has been replaced by zeros in the wavelet domain, is from a low spatial resolution, then the corresponding higher resolution lines covering the same spatial position must have lower than or equal SNR. Therefore, they are not acquired and filled with zeros in the wavelet domain [3, 4]. This results in an SNR increase as lines with low SNR are removed. Only those containing significant signal, contributing to the image information, are retained. In addition, since a given number of wavelet lines are not acquired, a reduction in acquisition time is obtained termed as T_{red} , according to:

$$T_{red} = N * TR - (n * TR) \quad (3)$$

where n is the number of acquired wavelet lines, TR is the recovery time and N is the total number of wavelet lines.

By including the acquisition time reduction approach described in reference [7] into the MR sequence proposed here, the total number of wavelet lines N is split into M lines acquired using the full TR and K lines acquired using the effective TR , termed as TR_{Min} . Similarly the number of acquired wavelet lines n is divided into M' lines acquired using the full TR and K' lines acquired using the effective TR , termed as TR_{Min} . As a consequence, the new acquisition time reduction is modified to:

$$T_{red} = (M - M') * TR + (K - K') * TR_{Min} \quad (4)$$

The equation above encompasses the advantages offered by wavelet encoding utilizing both spatial localization excitation and wavelet coefficient removal due to low SNR. These two wavelet characteristics allow for reduction from full TR to Tr_{Min} due to the excitation of spatially localized sub-spaces [7] and pruning of some wavelet steps due to the low SNR.

MATERIALS AND METHODS:

The proposed de-noising method is developed by modifying the GE-WE sequence to perform the de-noising during the feedback process after the acquisition of each wavelet line. The GE-WE 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.

An appropriate threshold function containing the threshold method is inserted into real time feedback code of the ICE (Image Calculation Environment) of the GE-WE sequence. The threshold function acts in the following manner.

The sequence reads the experimentally determined value of *val* from the control panel. The sequence then multiplies this value by the average of the acquired wavelet line. If this value is greater than the maximum signal intensity of the line, then the line is presumed to have no useful signal. It is substituted by zeros in the wavelet domain and the corresponding higher resolution lines are not acquired [8]. Otherwise, the line is presumed to have significant amount of signal and recorded in the wavelet domain.

In simulation, the wavelet transform using Haar wavelets as implemented in the GE-WE sequence is performed on an input image. The de-noising algorithm as above is tested on the resulting wavelet domain lines as follows.

For each wavelet resolution (dilation), the de-noising algorithm detects the maximum signal intensity in that entire resolution termed as *maxValue*. It then sets to 0 any point below the ratio *maxValue* / *val*, and sets a flag indicating that the point has been set to 0.

RESULTS:

Figure 1 shows the spherical water phantom images (diameter 150 mm) obtained using the GE-WE sequence with (Fig. 1B, 1C) and without (Fig. 1A) the de-noising approach. No significant increase in SNR has been obtained in this phantom study. The time taken for Fig. 1A, 1B, and 1C was 64s, 61s and 57s, respectively, leading to a reduction in acquisition time of about 3s (5%) (Fig. 1B) and 7s (11%) (Fig. 1C). These results have been obtained with a threshold value set to 0, 50, and 75 a.u., for Fig. 1A, 1B, and 1C respectively. One should notice minimum alteration in image quality occurring at threshold of 75. Figures 1D, 1E, and 1F display the zoomed upper left region of the images in Figures 1A, 1B, and 1C, respectively. The acquisition parameters are as follows: FOV = 180 mm, slice thickness = 10mm, TE/TR = 10/500 ms, image size = 128 x 128. The threshold value is set to 0 a.u. for Figure 1A, 50 for 1B, and 75 for 1C.

Figure 2 shows the simulated results of a standard ACR (American College of Radiology) head coil phantom. The number of acquired lines is reduced from 128 lines (Fig. 2A) to 92 lines (Fig. 2B), when activating the thresholding technique by varying the threshold value from 0 (Fig. 2A) to 3 a.u. (Fig. 2B). A decrease of 28% in acquisition time is obtained.

Figure 3 shows the results on a simulated spherical phantom with an added zero mean Gaussian noise. Figures 3A and 3B show the noise reduction in an area of complete noise (the top left of the image in Figure 3E), while Figures 3C and 3D show the preservation of the detail on the edge of the shape. A factor of three in SNR increase is approximately obtained in this simulated data.

Table 1 shows the results of various SNR tests for different amounts of added zero mean Gaussian noise on the spherical phantom shown on Figure 3.

DISCUSSION:

The tradeoff that results from the increased SNR in the simulation is a slight loss of detail and resolution in some parts of the image. Areas of high contrast remain sharp, but some detail may be lost in areas of the image that are less distinct [8]. If the noise is relatively low, as it is in the phantom images, the results are nearly indistinguishable. However, as the noise increases, more lines are skipped, and this result in a loss of details as displayed in Figure 1.

Thus, the quality of the phantom results is dependent on the threshold value selected by the user. While this allows for more control over the process, if selected improperly, this could lead to suboptimal image quality or a higher than necessary acquisition time. For this reason, future implementations could automatically select the best threshold value to use in order to preserve the image quality while reducing the acquisition time as much as possible. Possible alternative and powerful thresholding methods are the Curvelet and Ridgelet techniques [9].

The proposed technique fails in providing accurate results in the following case. If an image is perfectly symmetrical in the WE direction at any given resolution, the signal will cancel itself out and the data will have a low SNR. Therefore, no further lines at

higher resolutions will be acquired, potentially missing details that would only be present at higher resolution lines. While this is likely to happen in theory or other types of images, it is very difficult to occur in MRI, due to minor fluctuations in the field and the region to be imaged producing signals with different intensities making imaging a perfectly symmetrical region very unlikely to happen.

CONCLUSION:

The main objective of this work is to show that post-processing de-noising methods could be used in real time to not only to improve the SNR but also to simultaneously reduce the acquisition time in wavelet encoding imaging sequences such the GE-WE small FOV imaging technique. In phantom studies acquisition time reduction ranging from 5 to 10% has been obtained, with no image quality degradation. Simulation results show that the SNR can be increased up to a factor of three with no alteration of image information. Further tests on complicated phantom shapes are necessary to confirm and improve the obtained results by investigating more sophisticated thresholding algorithms.

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